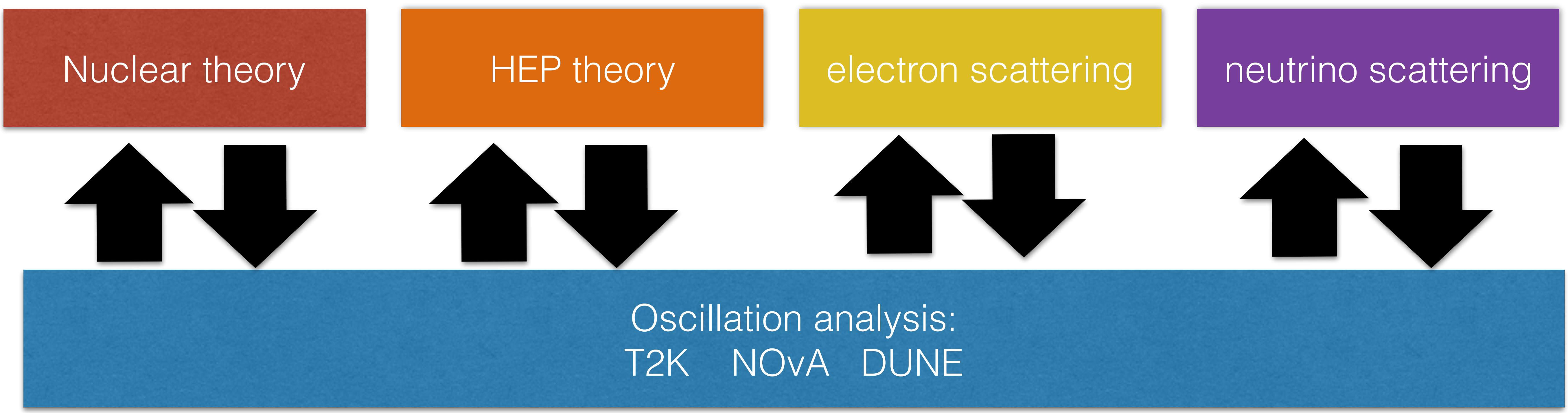
Neutrino interaction uncertainties in current and future experiments

What are the critical interfaces between theory/experiment?



Kendall Mahn
Michigan State University

How does neutrino interaction modeling affect oscillation analyses?

Sound Transit rendering of bridge between UW Station and campus

Disclaimers

I may use a lot of experimental specific jargon or imprecise language. Please let me know if what I say is unclear.

How does neutrino interaction modeling affect oscillation analyses?

Inputs:
Nuclear theory
HEP theory
Electron scattering
Neutrino scattering

Oscillation analyses

Sound Transit rendering of bridge between UW Station and campus

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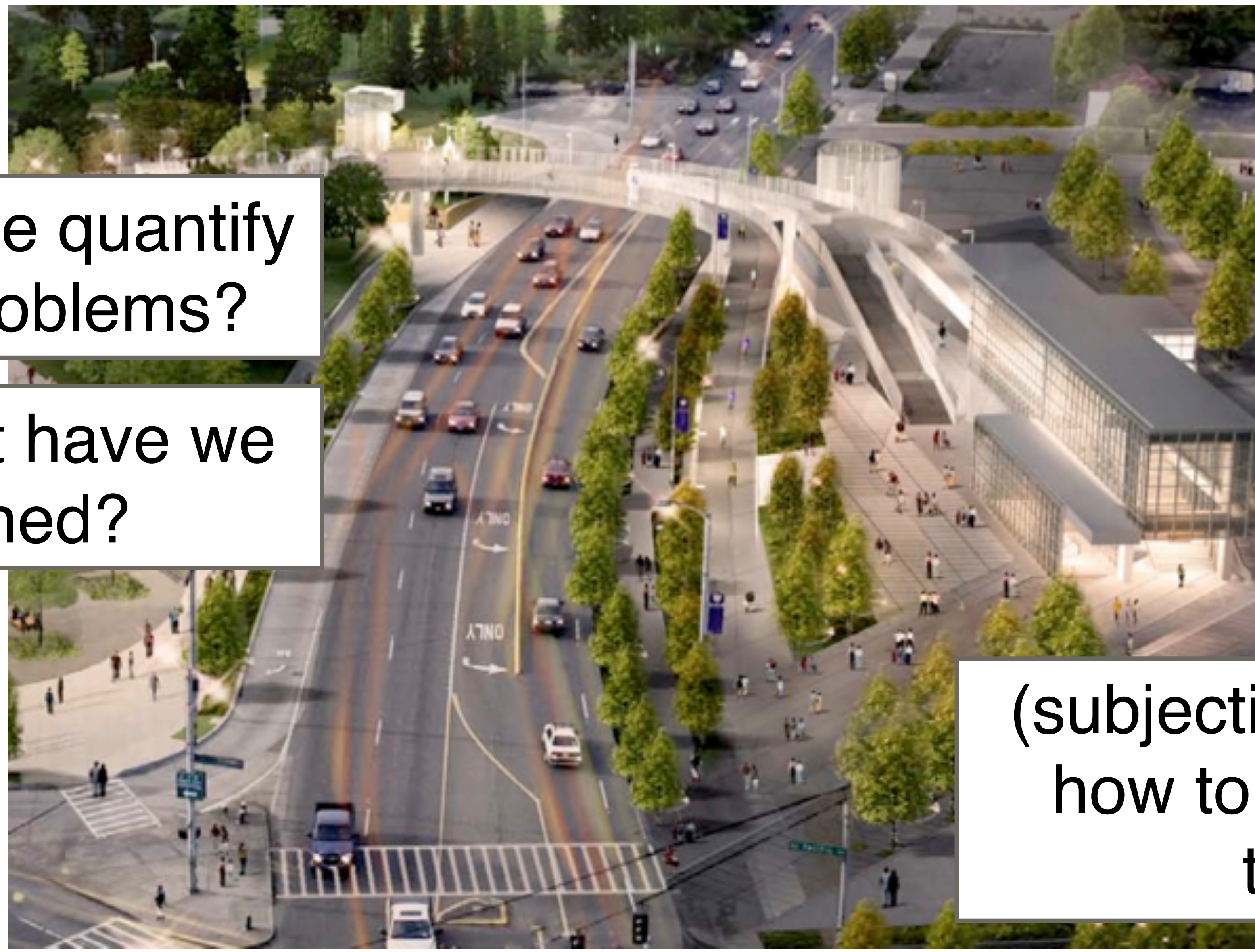
Sound Transit rendering of br
Station and car

How does neutrino interaction modeling affect oscillation analyses?

What are the possible problems?

How do we quantify those problems?

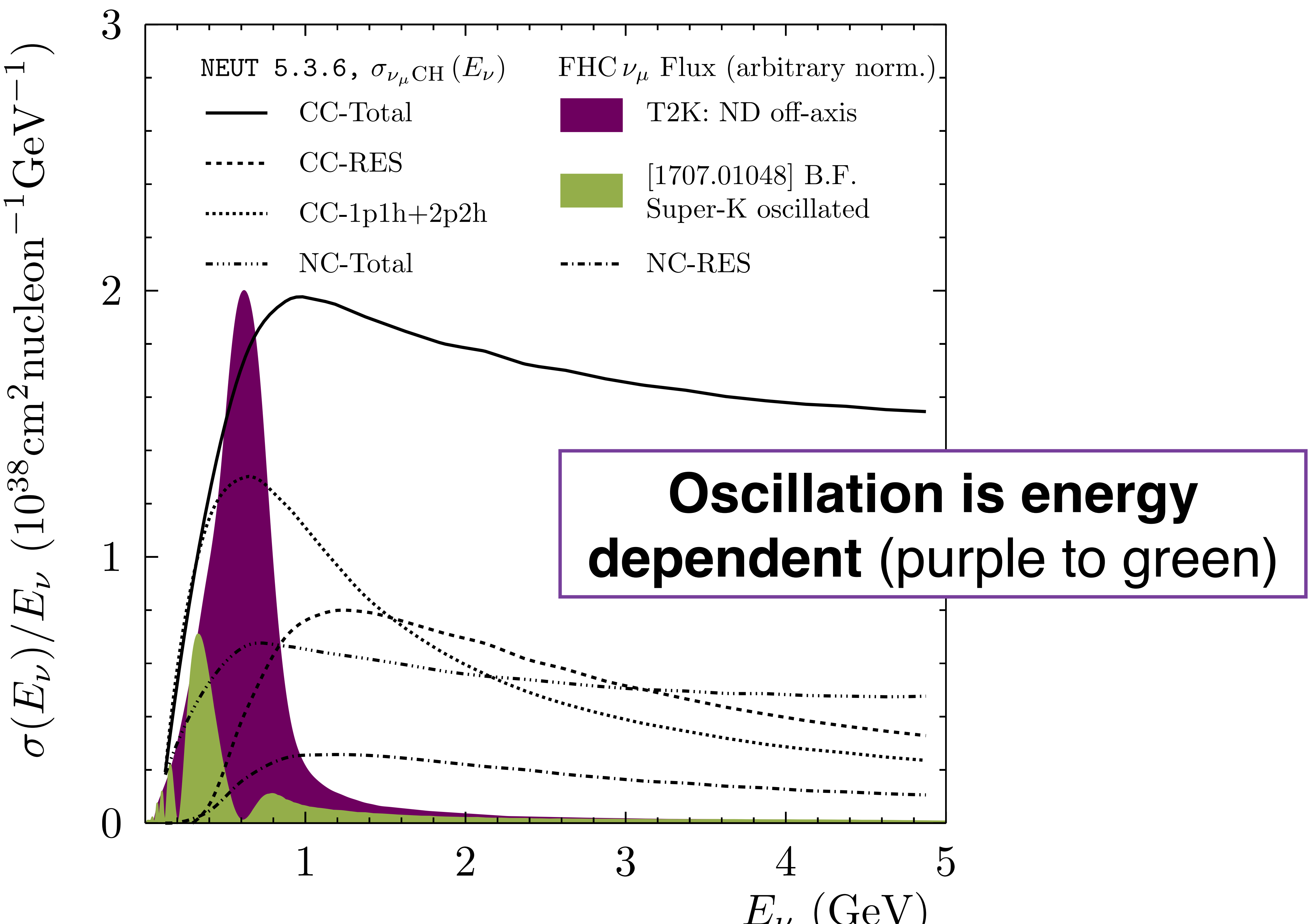
And what have we learned?



(subjective) ideas about how to move forward together

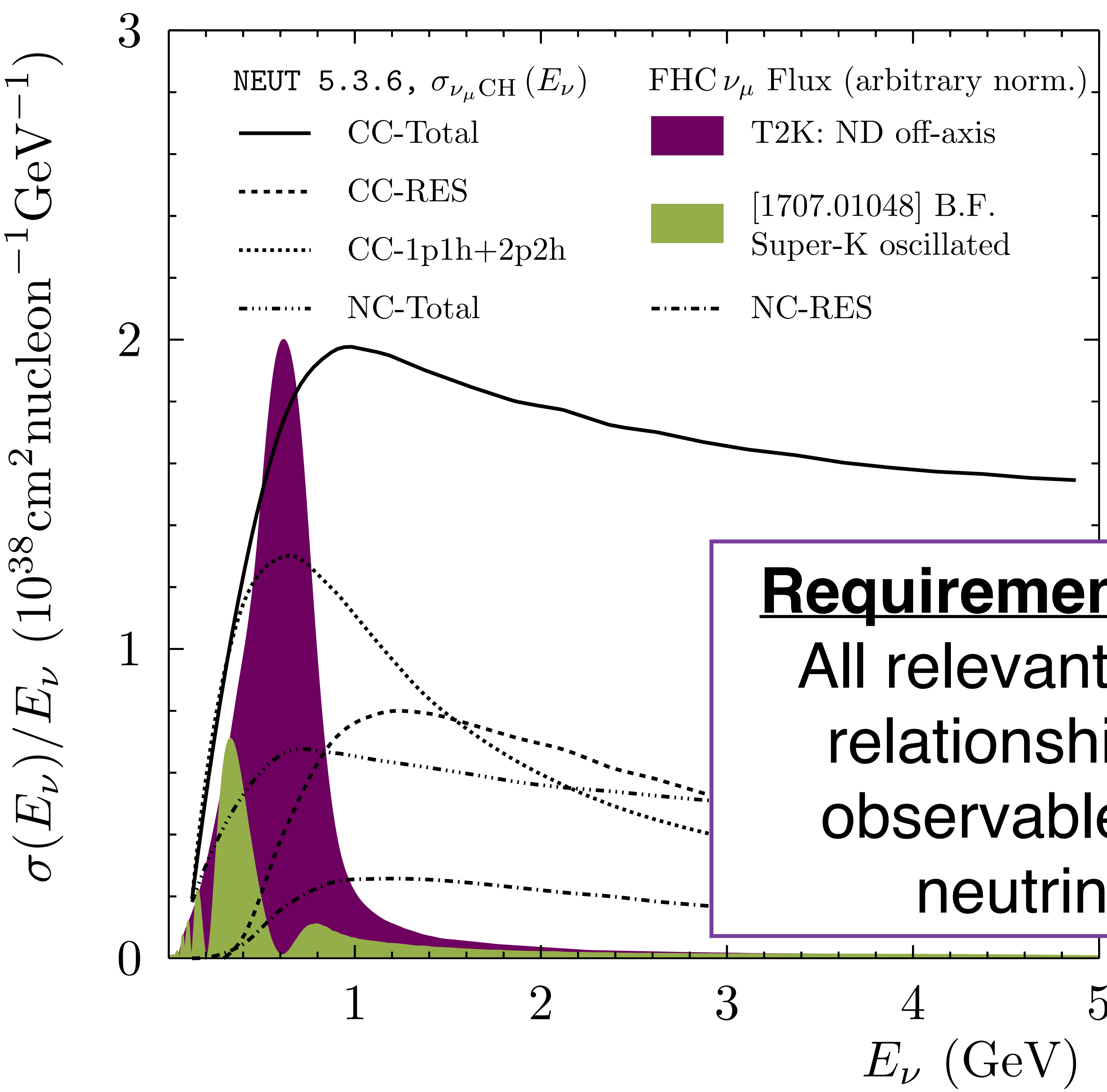
Sound Transit rendering of bridge between UW Station and campus

A neutrino flux and cross sections, overlaid



- Neutrino decay-in-flight beams are not mono-energetic
  - Spread of beam is larger than nuclear effects

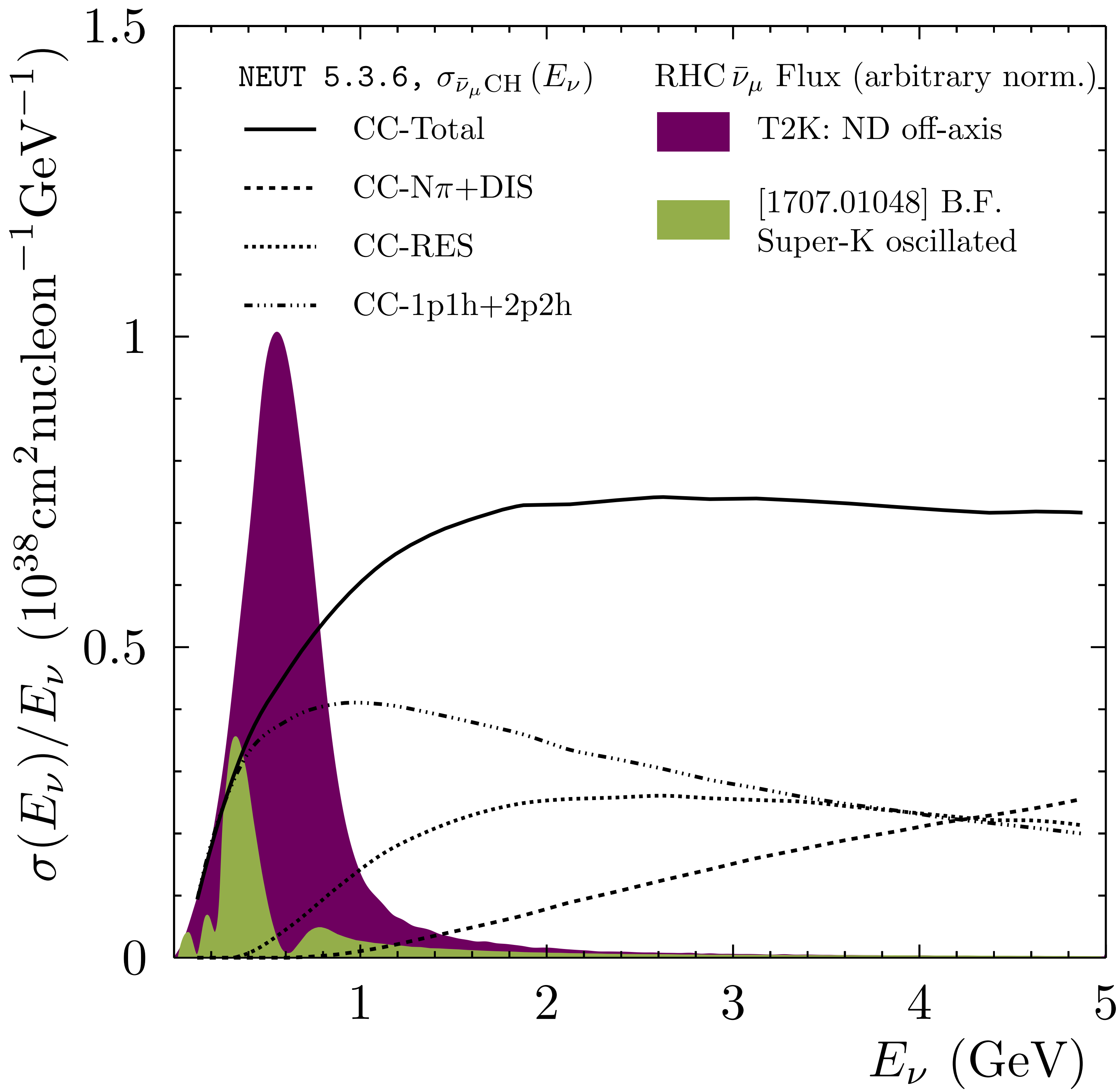
Can’t isolate single processes: “wide beams”



Requirement for model:
All relevant processes, relationship between observables and true neutrino every

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

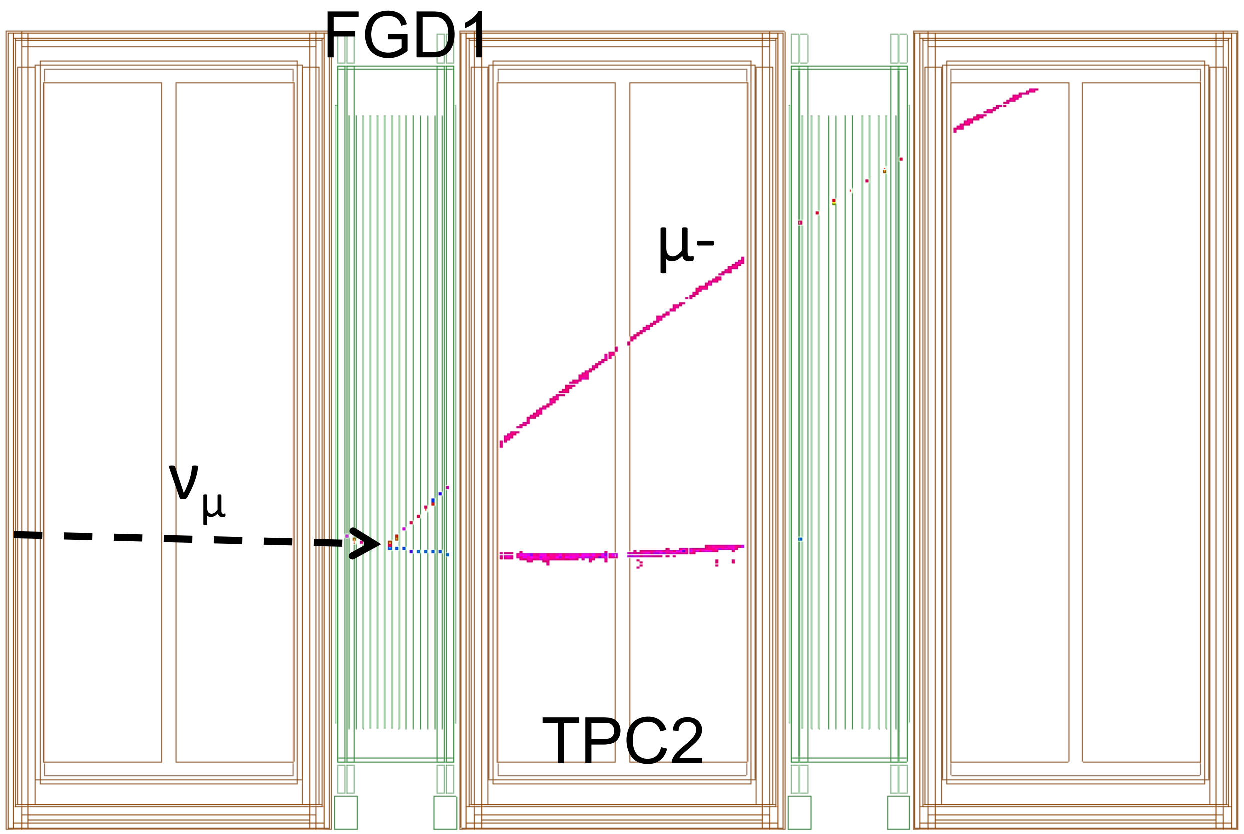
An antineutrino flux and cross sections, overlaid



Requirement for model:

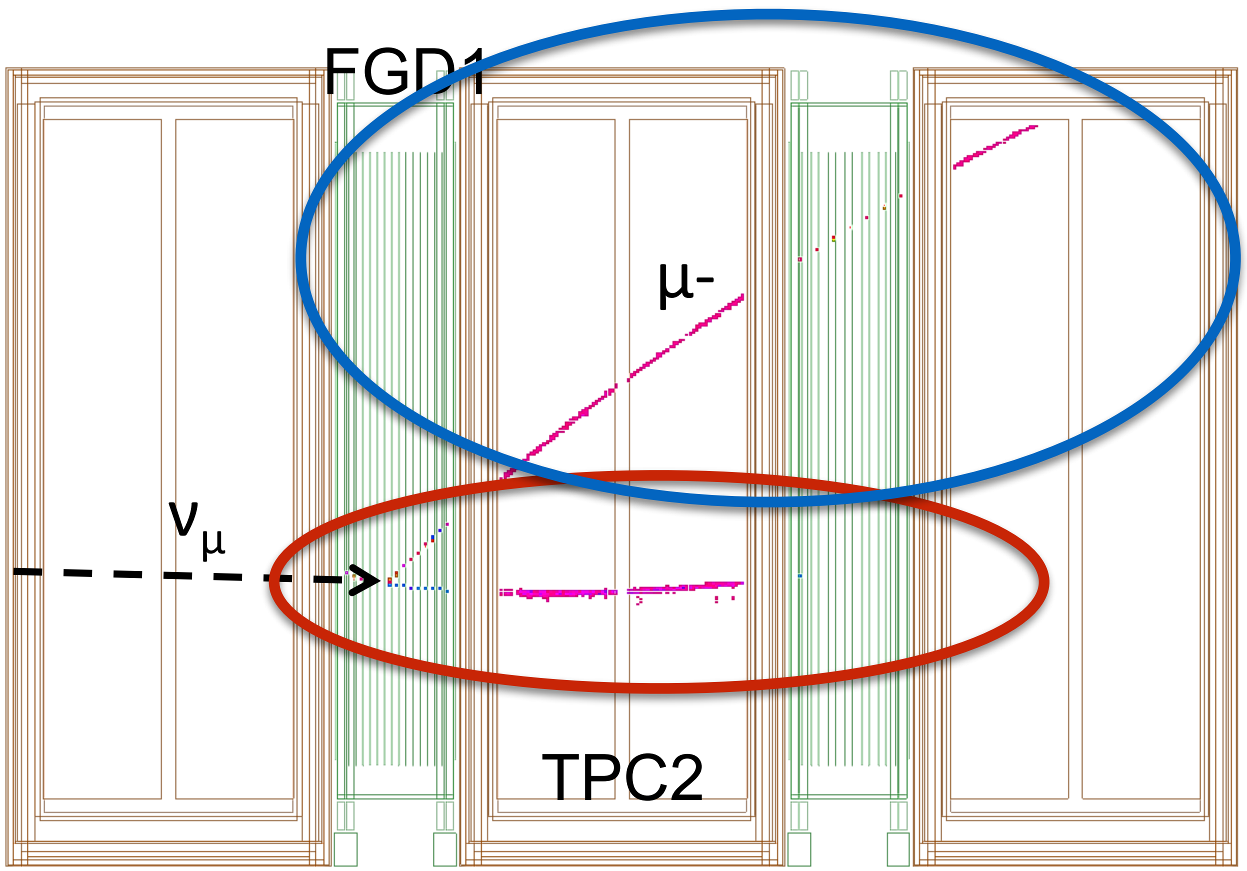
All neutrino flavors! (electron, muon and **antineutrinos**)

Example: process vs. topology



- Tokai-to-Kamioka experiment example
- CC0π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Needs: hadronic and leptonic state



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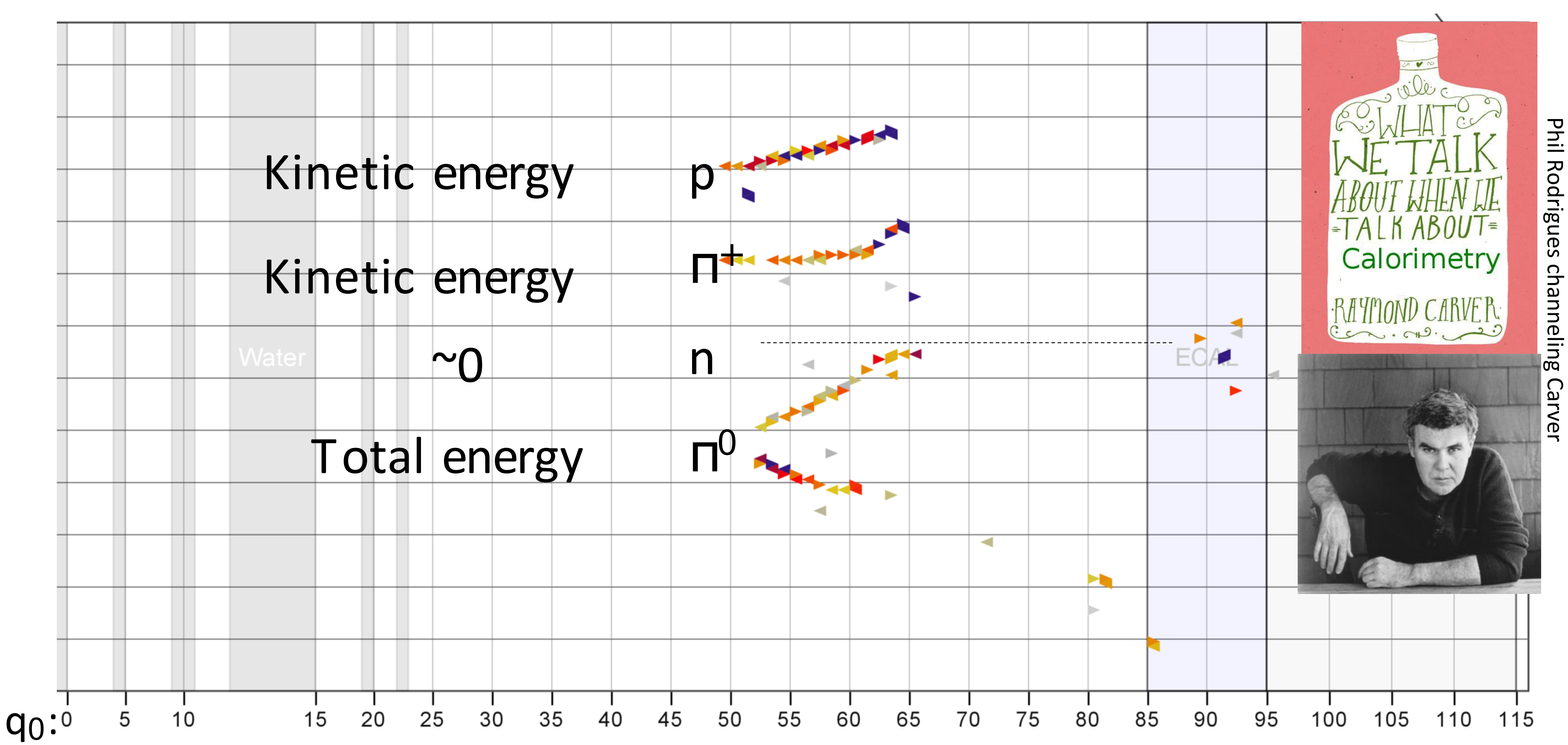
<u>Requirement for model:</u>
- All flavors, relevant processes
- All visible particles

What we mean when we say “visible energy”

Courtesy: Kevin McFarland, Phil Rodrigues

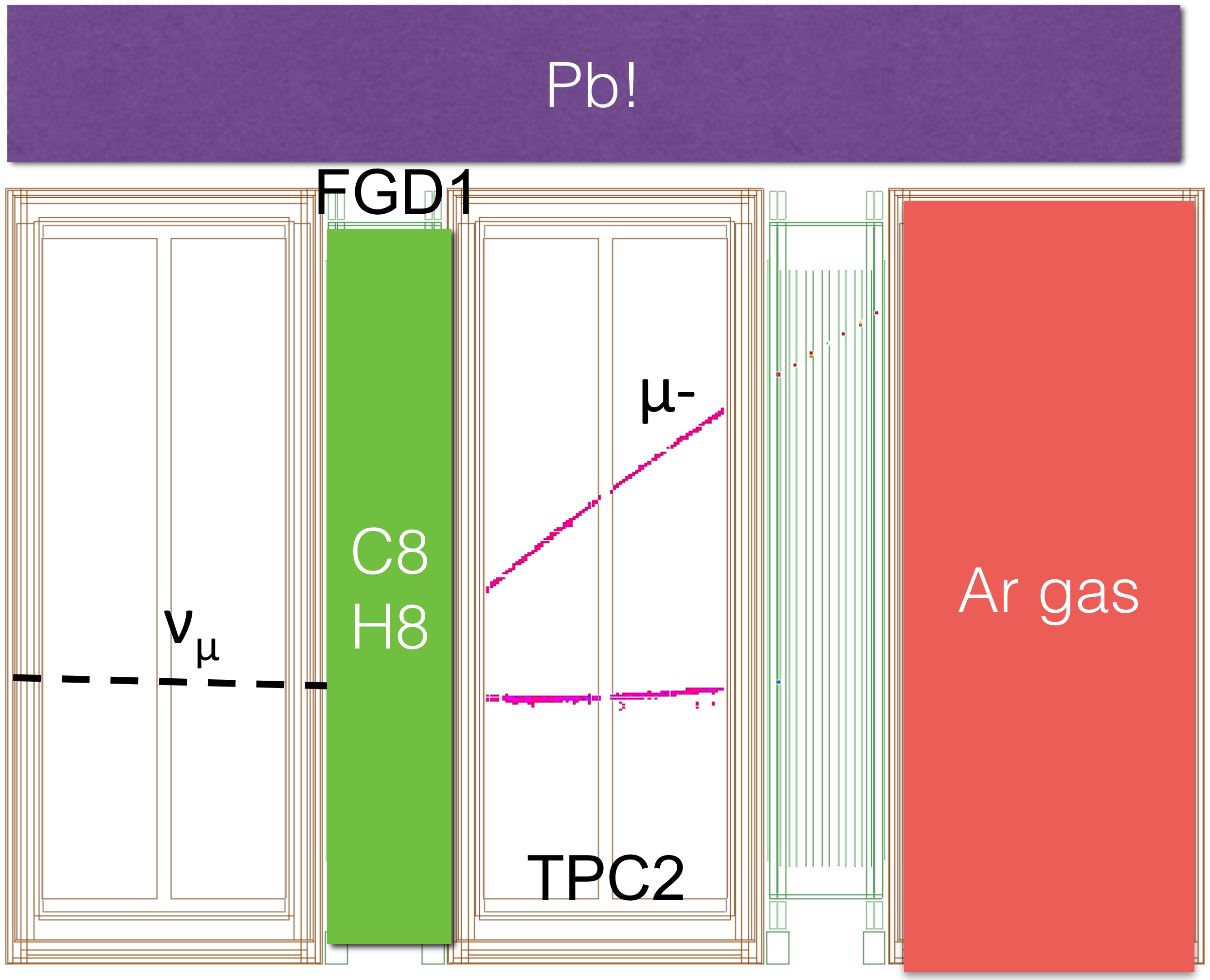


$E_{avail} \equiv$ (Proton and $\pi^{\pm}$ KE) + (Total E of other particles except neutrons)

April 2016 K. McFarland, Identifying Nuclear Effects @ MINERvA

Calorimetric detectors energy estimation depends on particle type -> exclusive

Needs: target material



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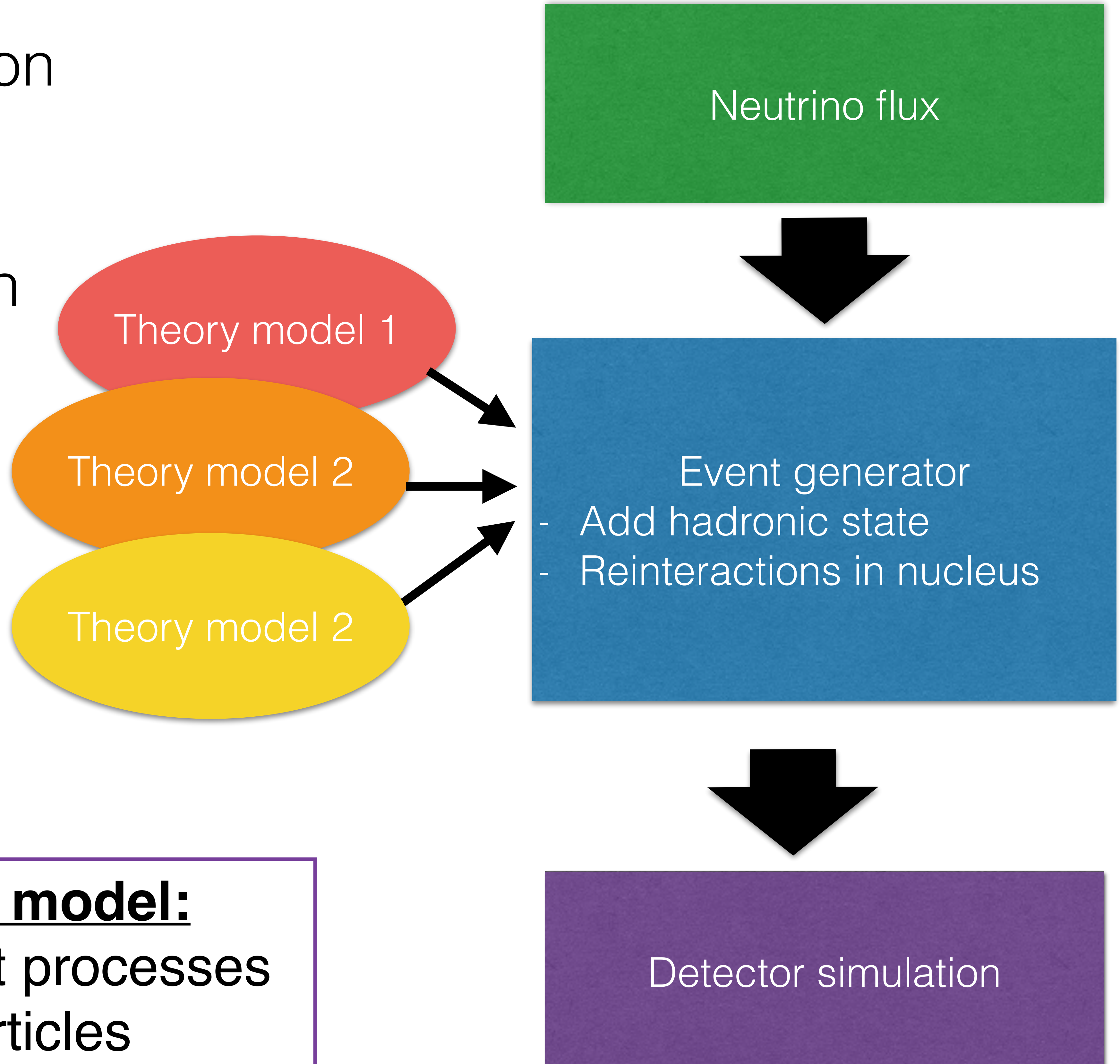
<u>Requirement for model:</u>

- All flavors, relevant processes
- All visible particles
- Most nuclear targets, esp C, O, Ar

“Generator”? What is that?

- Neutrino interaction models are embedded in software called an “event generator”

- Meets the requirements, provides tools to propagate uncertainty



<u>Requirement for model:</u>

- All flavors, relevant processes
- All visible particles
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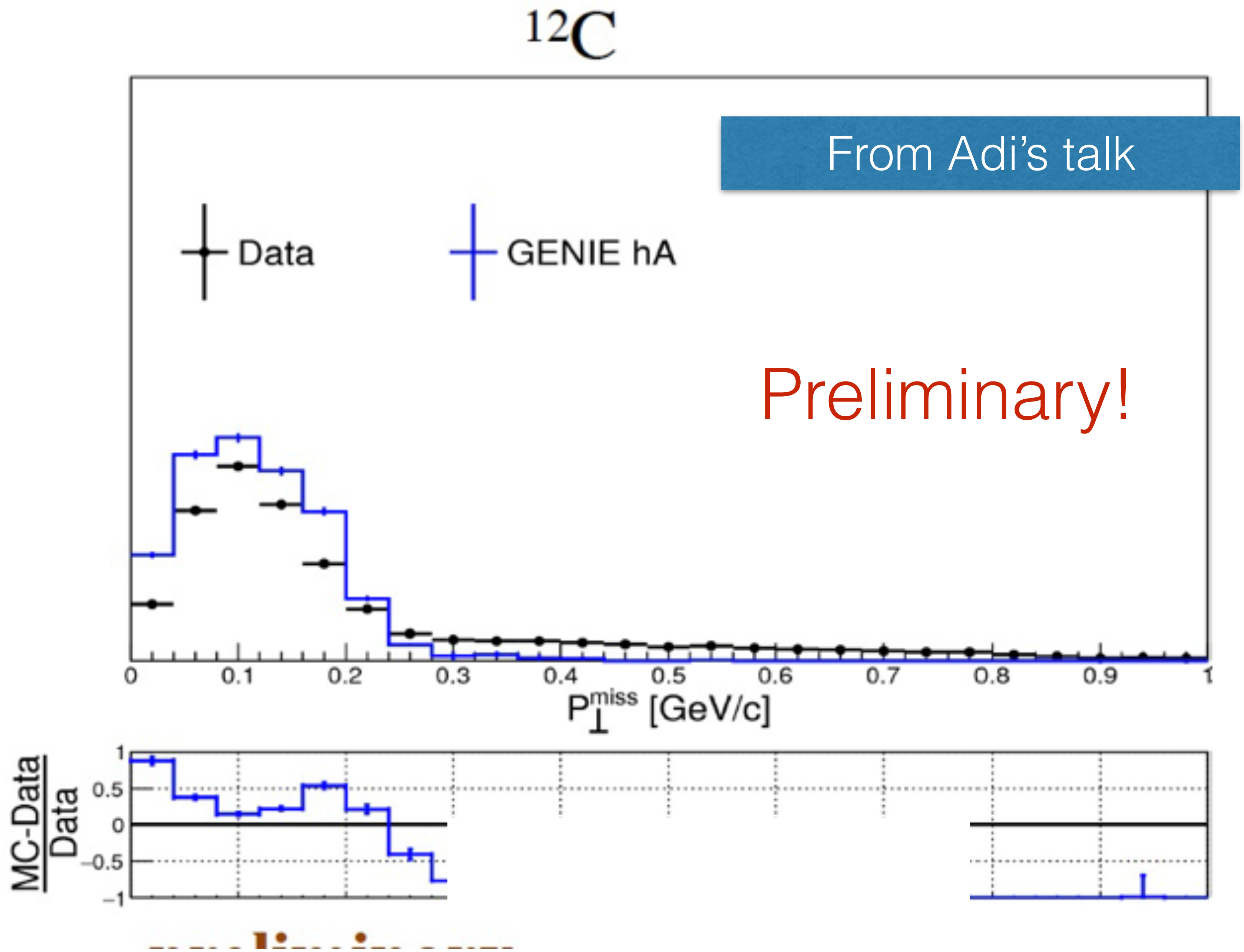
"Generator"? What is that?

- Neutrino interaction models are embedded in software called an "event generator"
- Meets the requirements, provides tools to propagate uncertainty
- but may make approximations, inconsistent choices



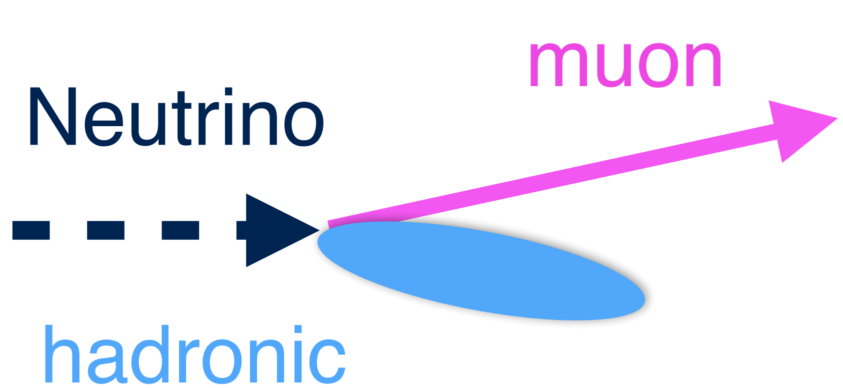
We must admit issues to move forward (and issues are not unique to one generator)
1) Is this important? 2) How to assess?

Energy estimators

- Oscillation depends on energy - *see Alex H.'s talk*
  - Estimate from hadronic and/or leptonic information

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

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



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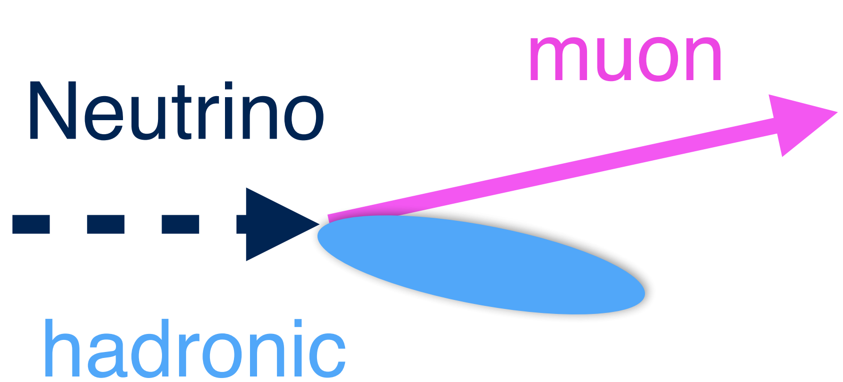
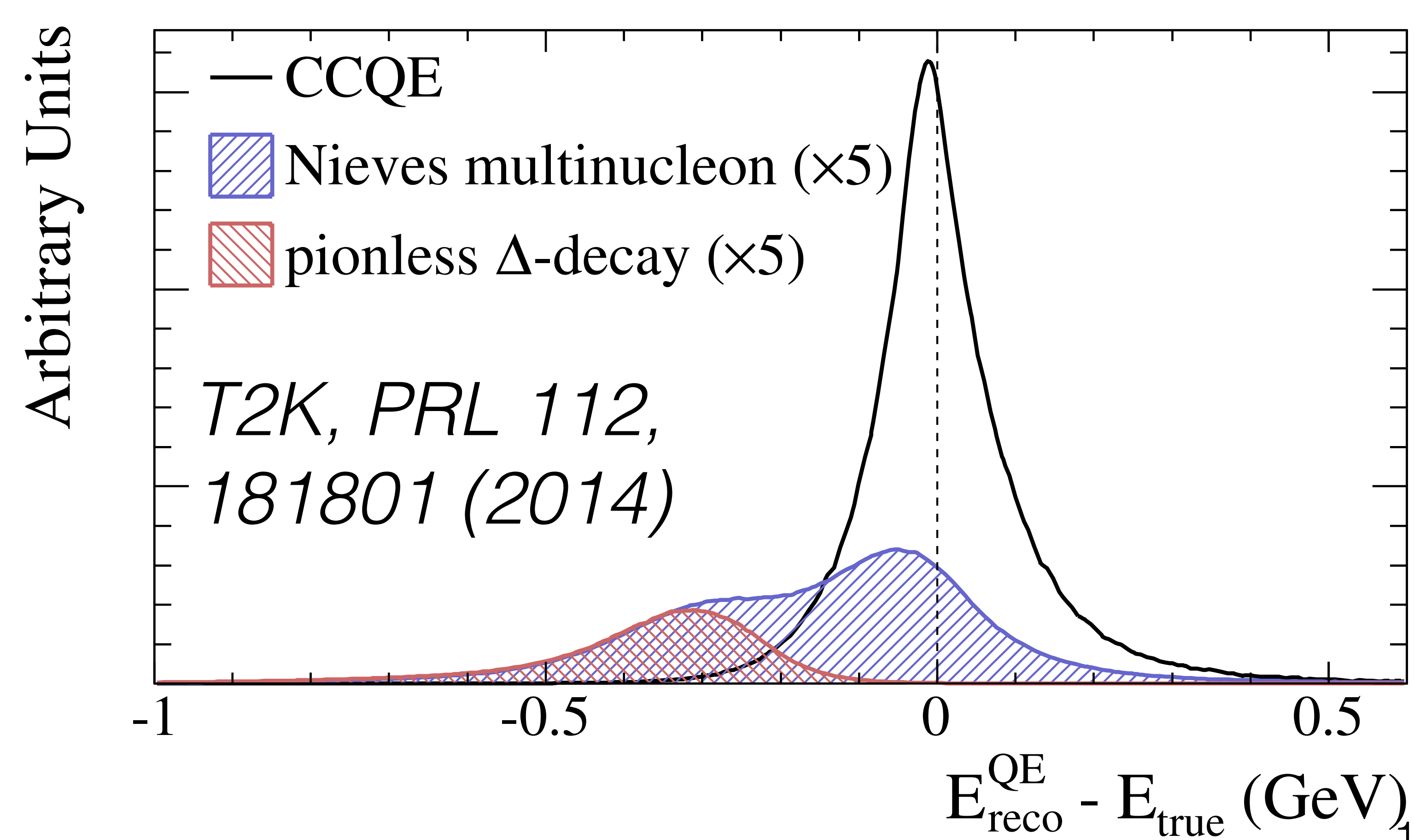
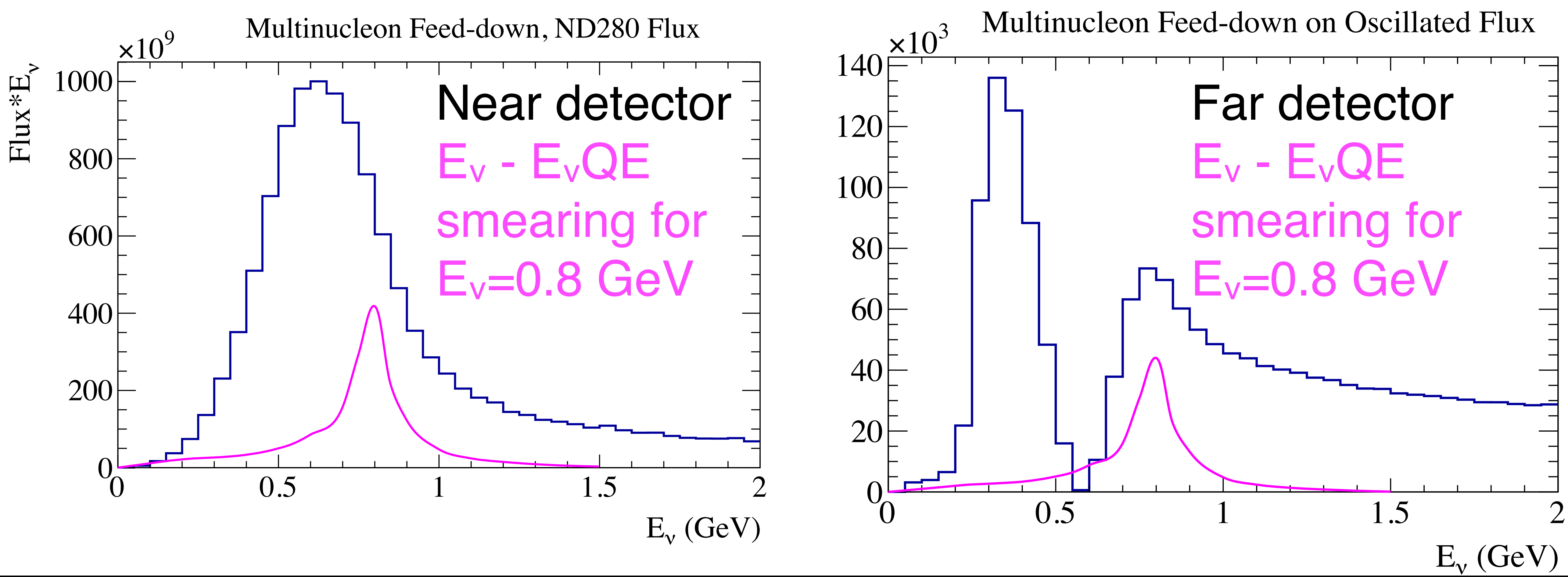
- Nuclear effects bias true and estimated neutrino energy





Even with a near detector, critical reliance on the model



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

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- QE method: 2p2h feed-down to oscillation peak from NuPRISM LOI: http://arxiv.org/abs/1412.3086
- Hadronic method: particle multiplicity, detection threshold

Summary: the possible issues

- Oscillation experiments need fully exclusive information

Summary: the possible issues

- Oscillation experiments need fully exclusive information
- Various inputs (theory, electron scattering, neutrino scattering) can help understand if our assumptions are sufficient for the models we use:
  - Relative strength of different processes (energy dependance, efficiency)
  - Energy estimation (hadronic state)
  - What parameterization+uncertainty is suitable

How does neutrino interaction modeling affect oscillation analyses?

How do we quantify those problems?

And what have we learned?

https://www.entropy.com.au/fun-factory-wooden-tool-box

T2K as an example

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$

- **Four flavors, five samples:** predominantly neutrino beam or predominantly antineutrino. ν_μ with no pion, ν_e with pion and without pion
- **Primarily CCQE, 2p2h, resonant pion production processes**
  - But, NC pion production backgrounds for both ν_e and ν_μ; photons mimic nue, pion may mimic ν_μ

T2K as an example

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All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- **Total uncertainty is about 5% - 18%, sample dependent**
  - Near detector reduces uncertainty by about a factor of ~2, recall wide flux, different acceptance, and ν_μ -> ν_e inferences

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T2K as an example

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SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
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- **Detector and final state interactions (pion reinteraction model)**

  Includes some cross section uncertainties, but this also lumps purely detector effects (e.g. secondary interactions) as both are tuned to external pion scattering data)

T2K as an example

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- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint** (limited by acceptance, different energy dependance)
  - Convolves input priors in a nontrivial way

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- Detector and final state interactions (pion reinteraction model)
- Near detector constraint (limited by acceptance, different energy dependance)
- Uncertainties which shift the relationship between true and reconstructed energy
  - Nucleon removal energy; Large uncertainty before upcoming e,e'p constraint
  - Other uncertainties ALSO shift the true-reco response — 2p2h (in ND) and FSI (top line)

T2K as an example

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- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
- **Differences between ν_μ and ν_e cross section**
  - See Kevin's talk, theoretically driven uncertainty, difficult to probe experimentally

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- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
- **Differences between ν_μ and ν_e cross section**
- **Single photon production -** difficult to measure at ND, small rate, large uncertainty

What is experimental interface to input communities?

- **What do we need to see out of oscillation experiments to determine what needs further study in the interaction model?**
- This is just overall normalization. We can also prepare “shape” figures of merit.
- *Q: What are the categories we need to see to better understand what matters?*
- *Q: And, what is possibly missing?*

What the community is worried about

From Nu-Print workshop: https://indico.fnal.gov/event/15849/timetable/#20180312

- What are the uncertainties needed for the 2p2h?
  - Large uncertainties on leptonic side (across q0-q3?). Differences between nu and nubar in overall strength.
  - What should be the hadronic final state association? And how much energy into (which) outgoing particles?
- Insufficiency of current resonance model to describe pion kinematics, low Q2 discrepancies.
  - Is 2p2h-like processes in resonance production?
  - Need NC for significant backgrounds (or exotic signals)
- Transition region! Incomplete experimental and theoretical footing
- Need heavier targets (Ar!) model efforts
- Nue/numu uncertainties
- *Kendall adds: NC diffractive processes not explicitly assessed*

"Fake data studies"

- Sometimes, it is not possible to incorporate into the analysis a new interaction model quickly. And, existing uncertainties may already cover the effect.

- To test the robustness of our oscillation analysis, we do "fake data studies" where:

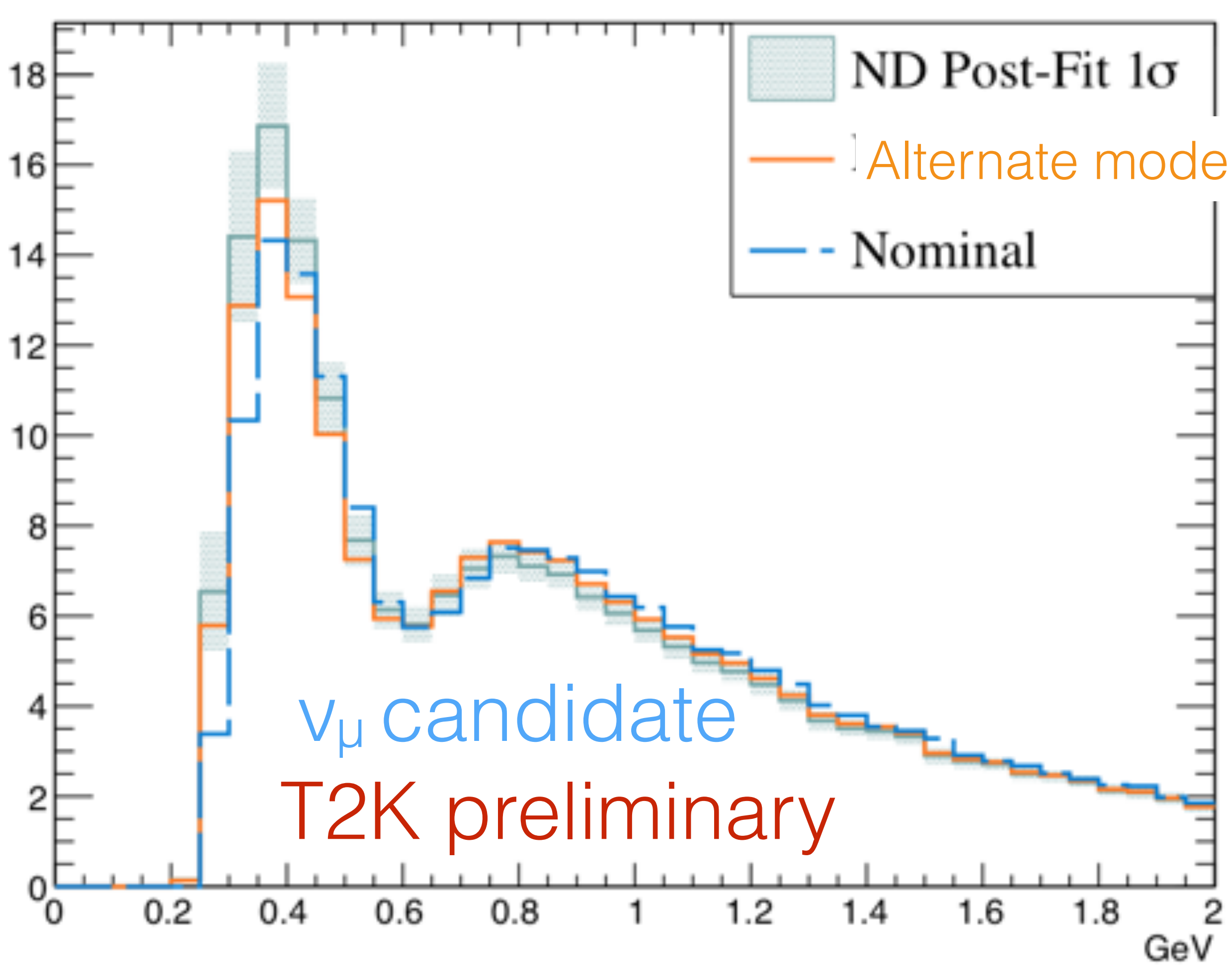
    - Prepare an alternate model, and include it in the analysis as if it were data

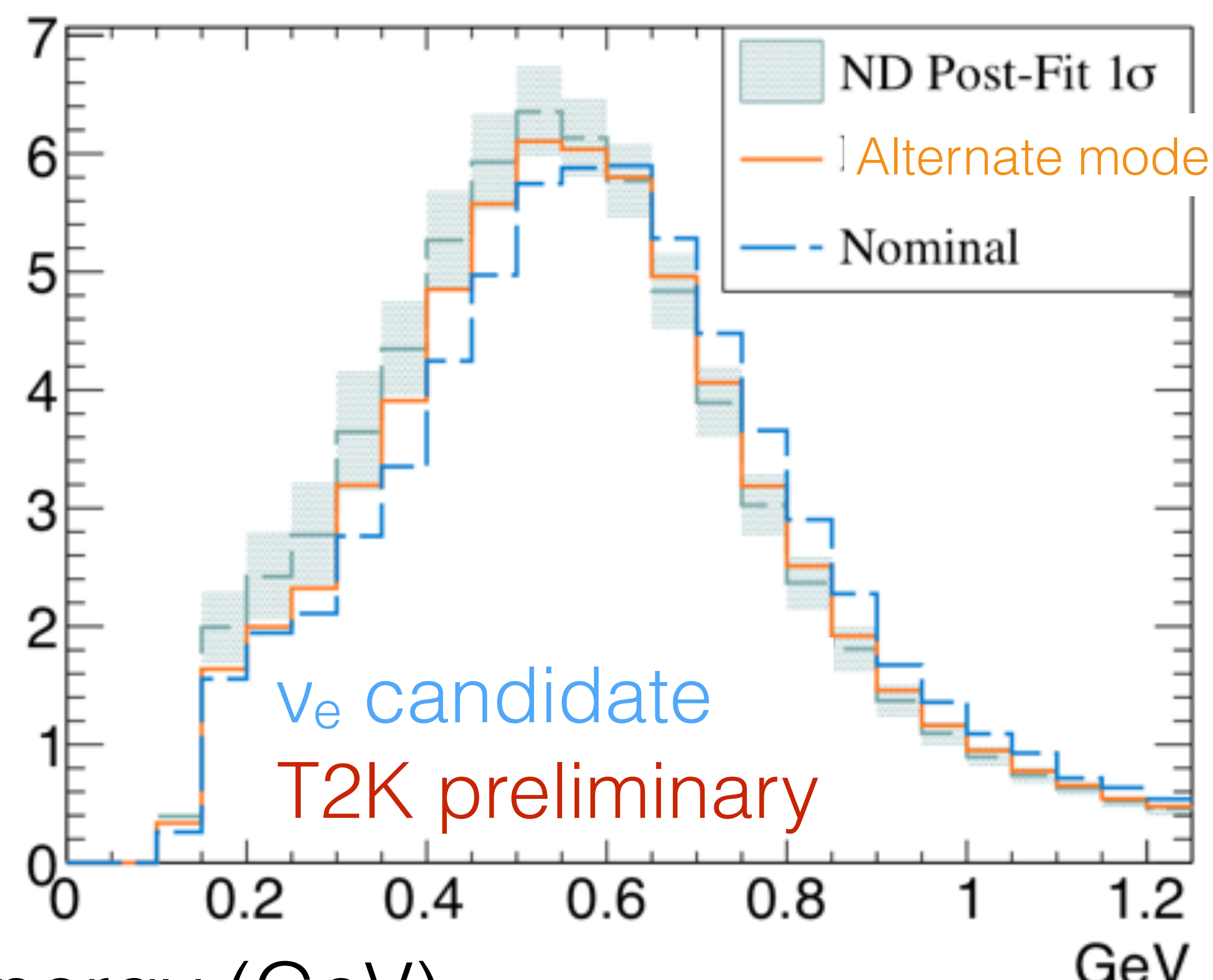
    - Run entire T2K oscillation analysis chain (fit near detector with nominal cross section uncertainties and propagate) to evaluate effect on oscillation parameters

    - If we see a measurable effect in the analysis, update systematic uncertainty.

An example "fake data study"

- 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





Reconstructed energy (GeV)

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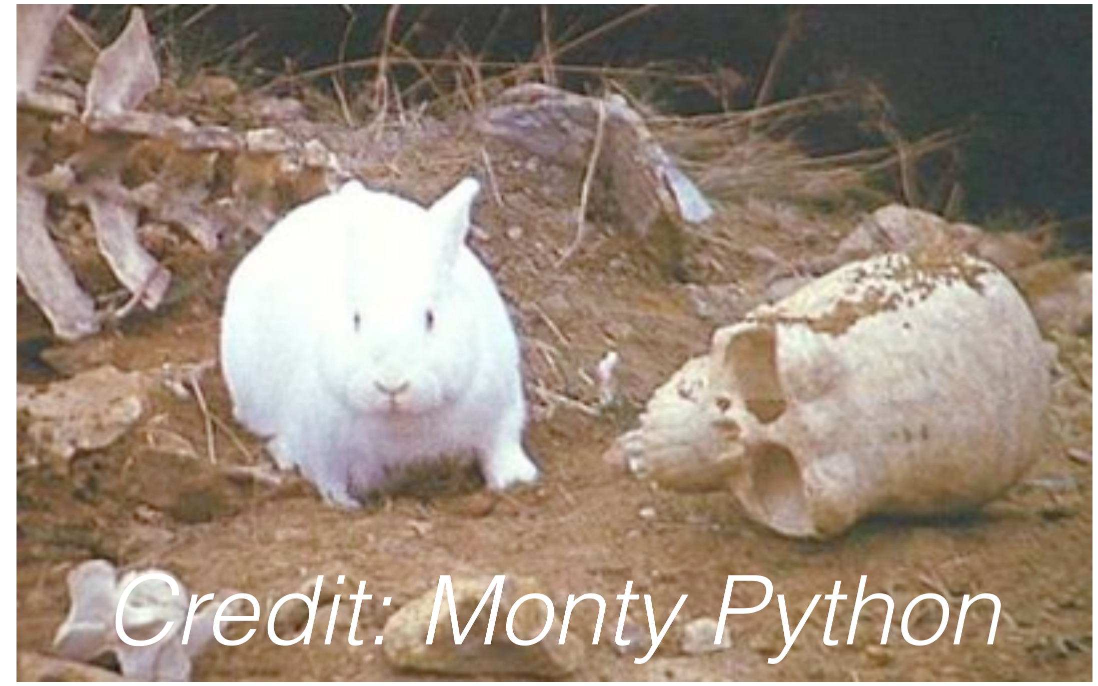
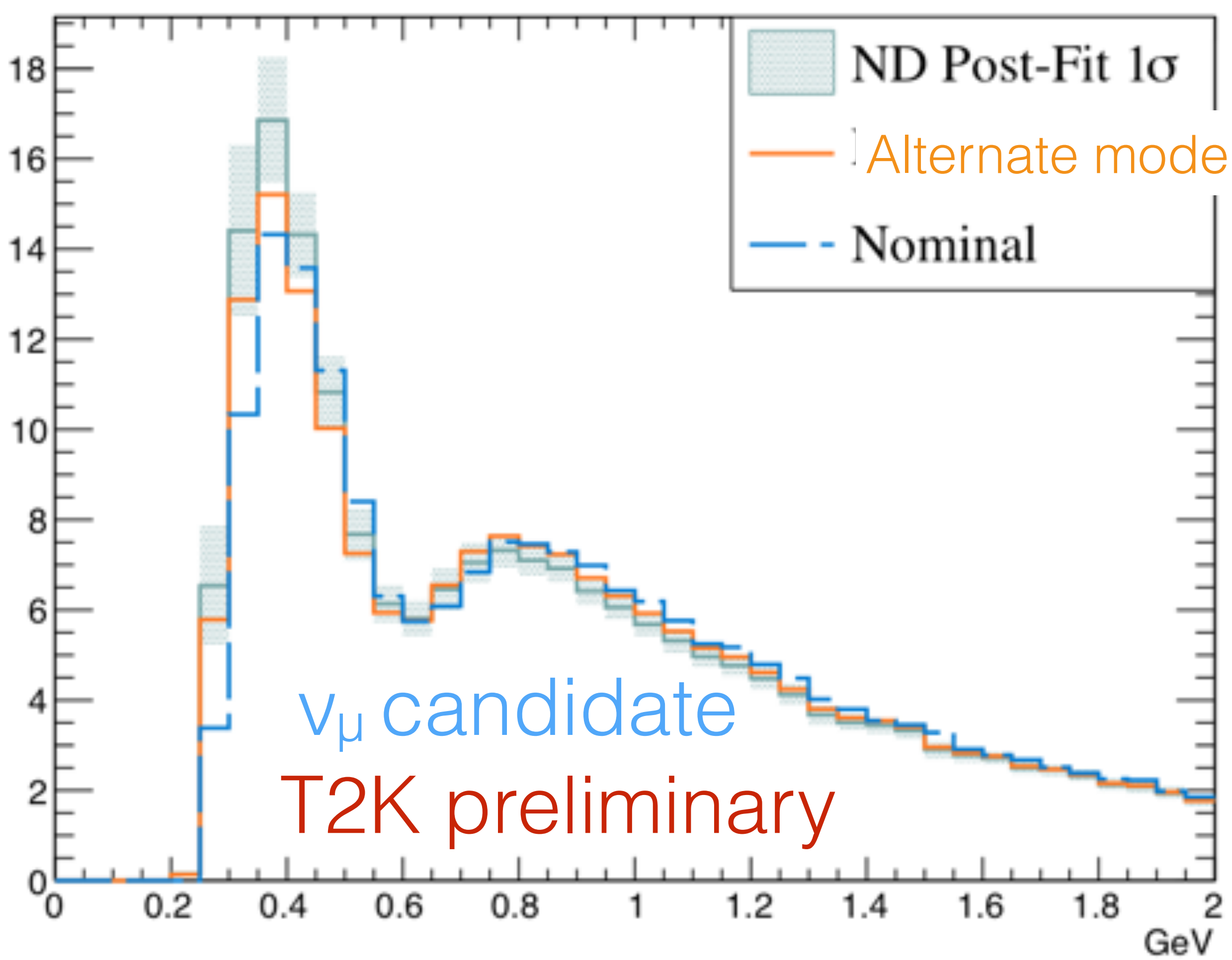
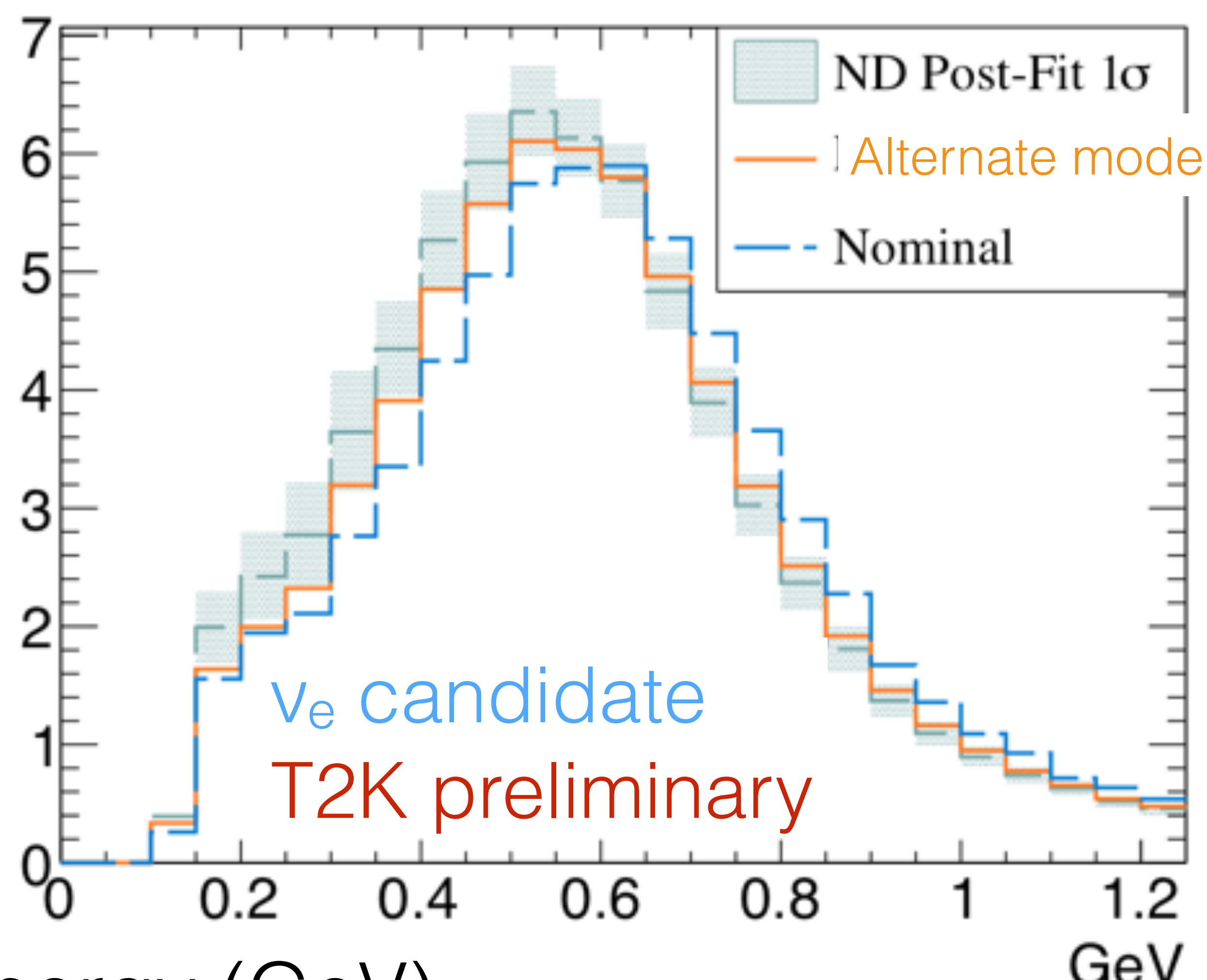


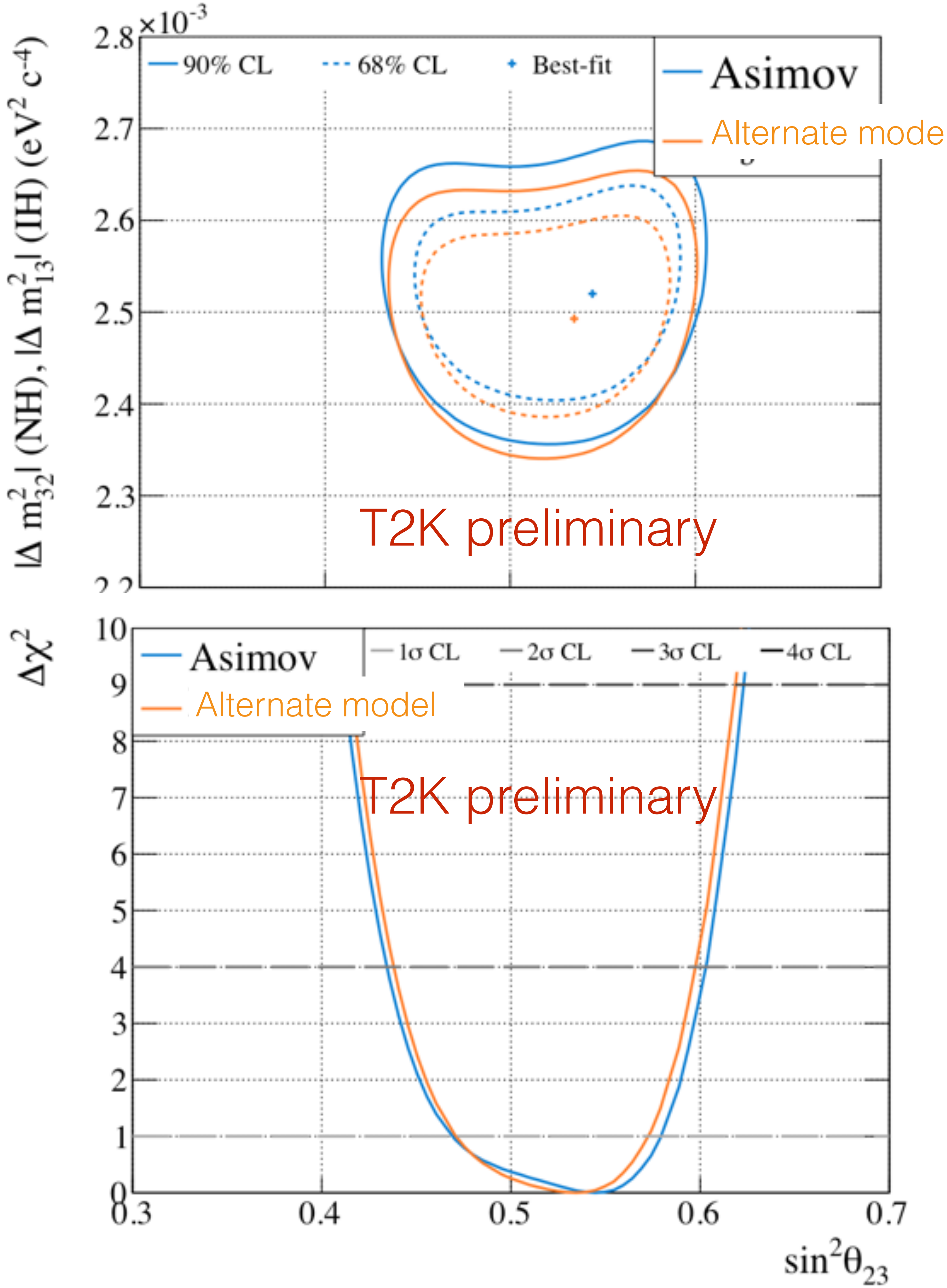




Reconstructed energy (GeV)

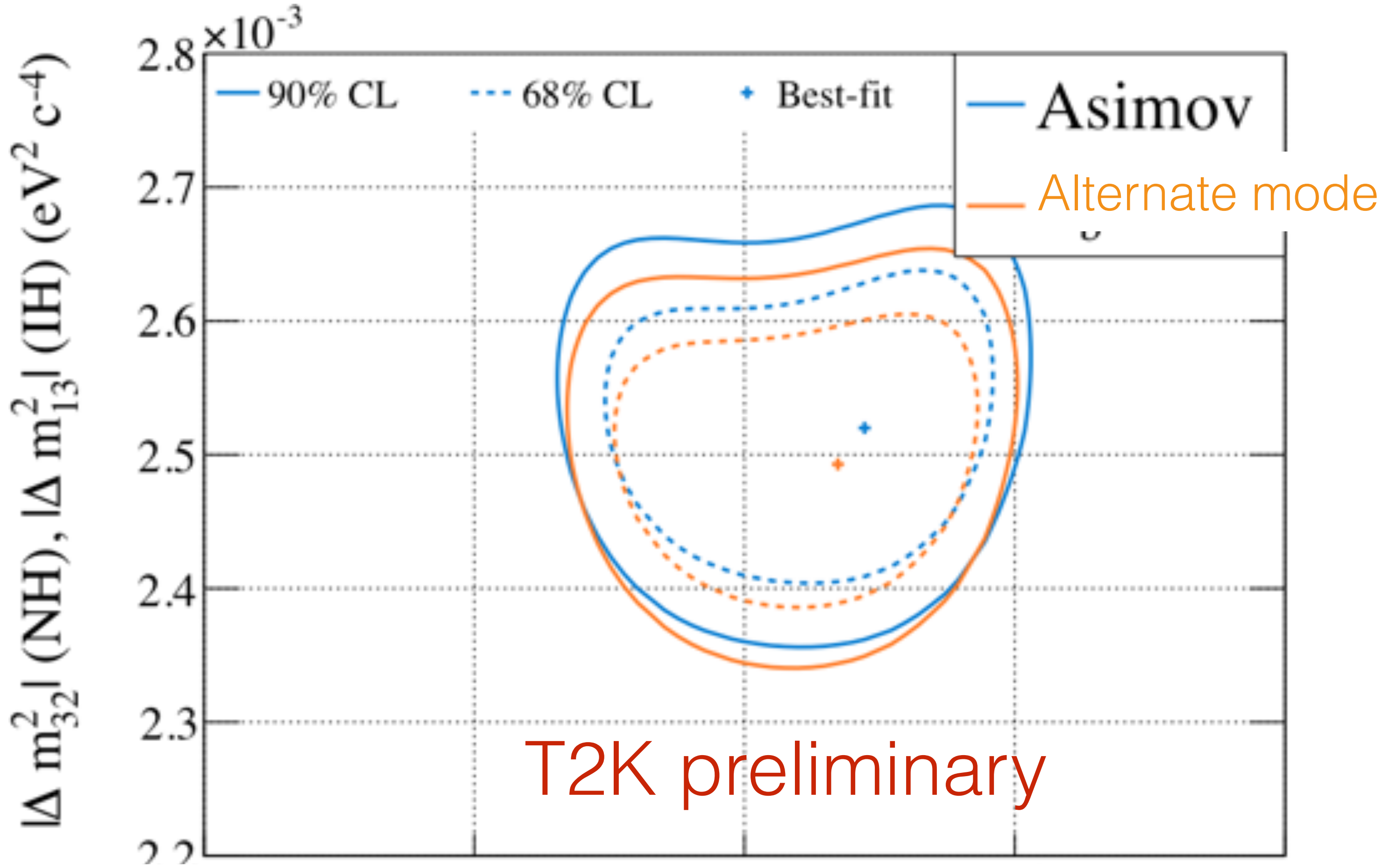
- Alternate models may create biases for current analysis; T2K adds additional uncertainty

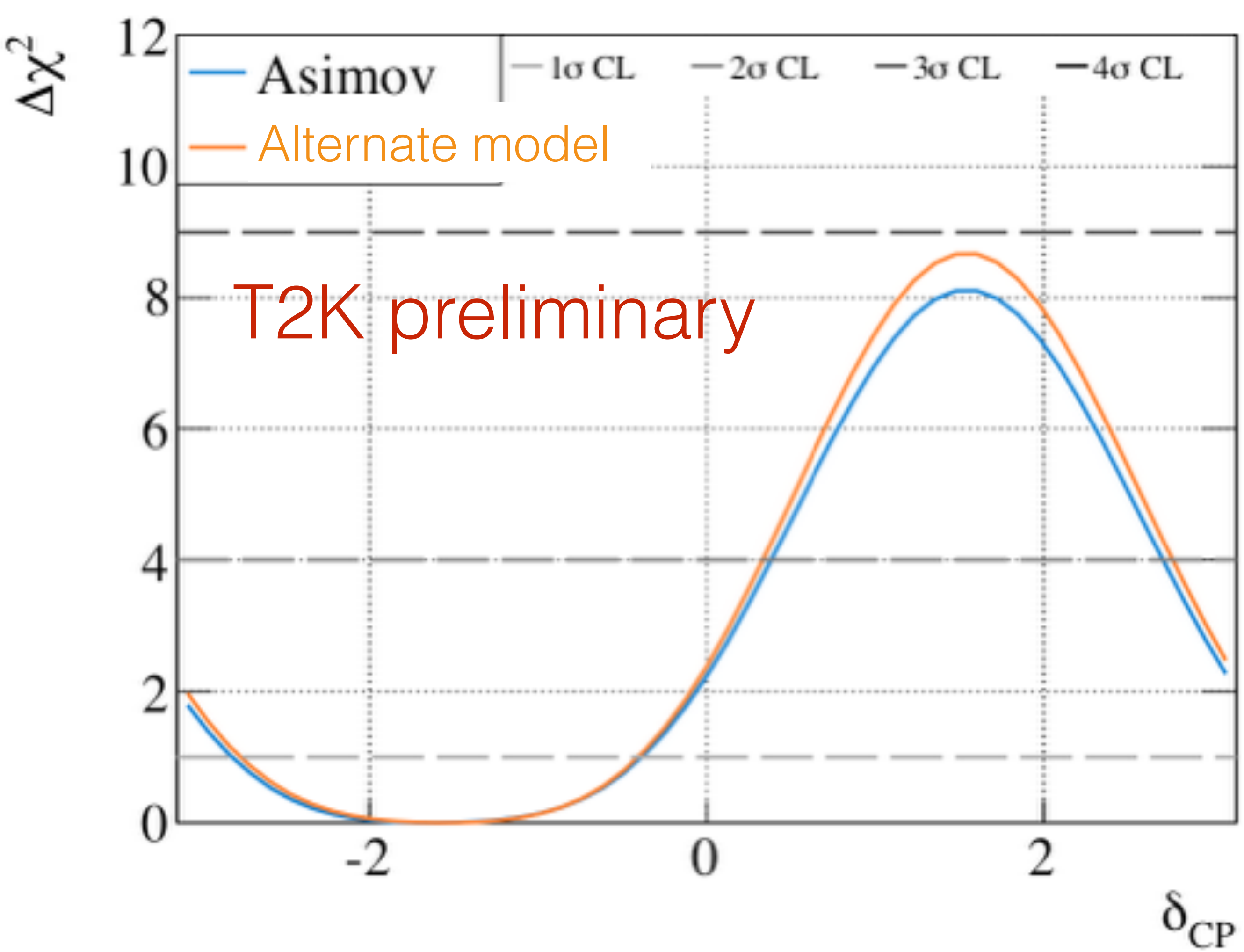
- We mustn't run away!

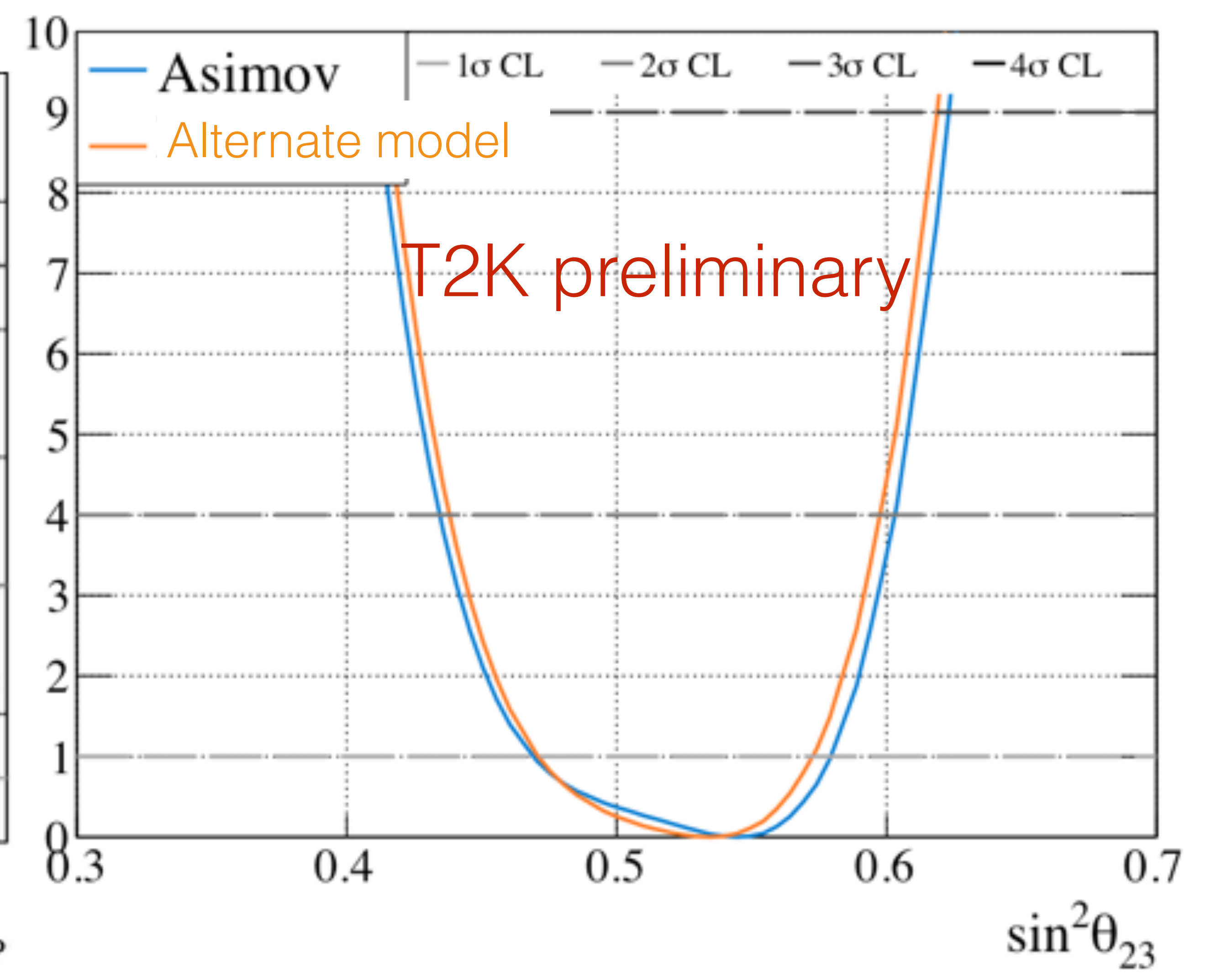


- Alternate models may create biases for current analysis; T2K adds additional uncertainty

- Effect depends on model (here, not much impact on δ_{CP})

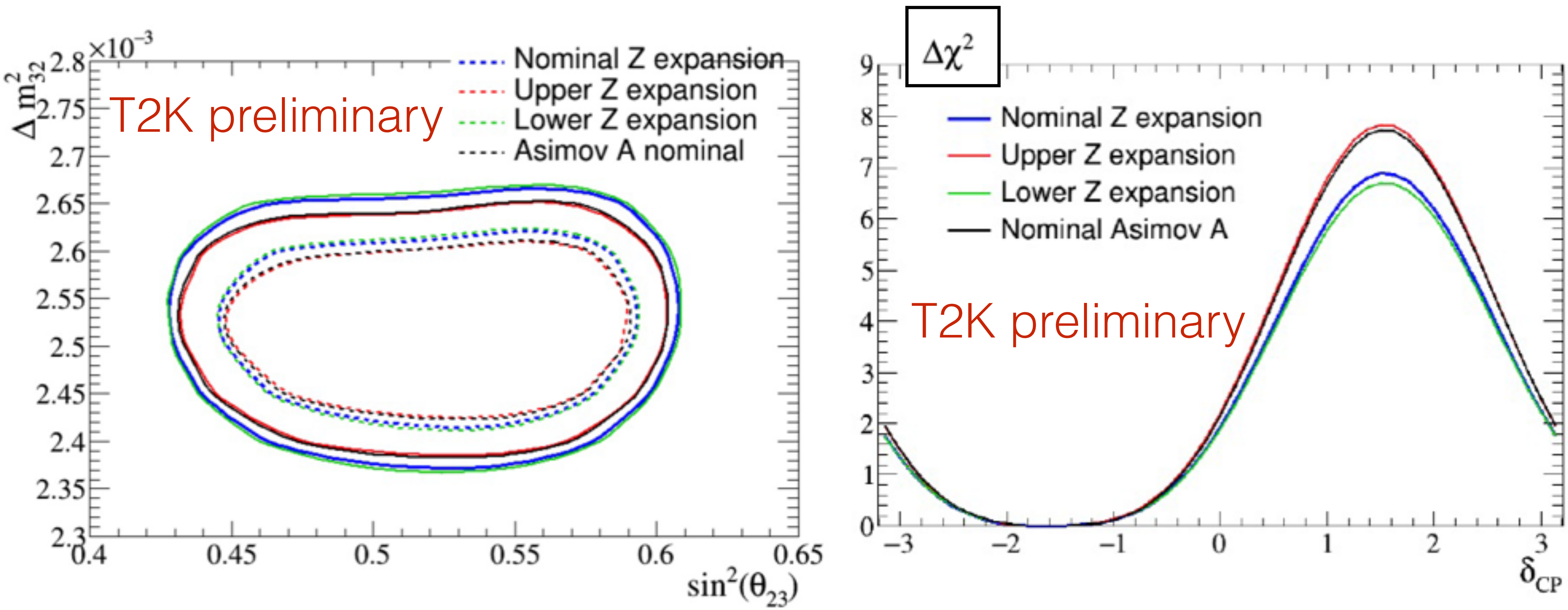






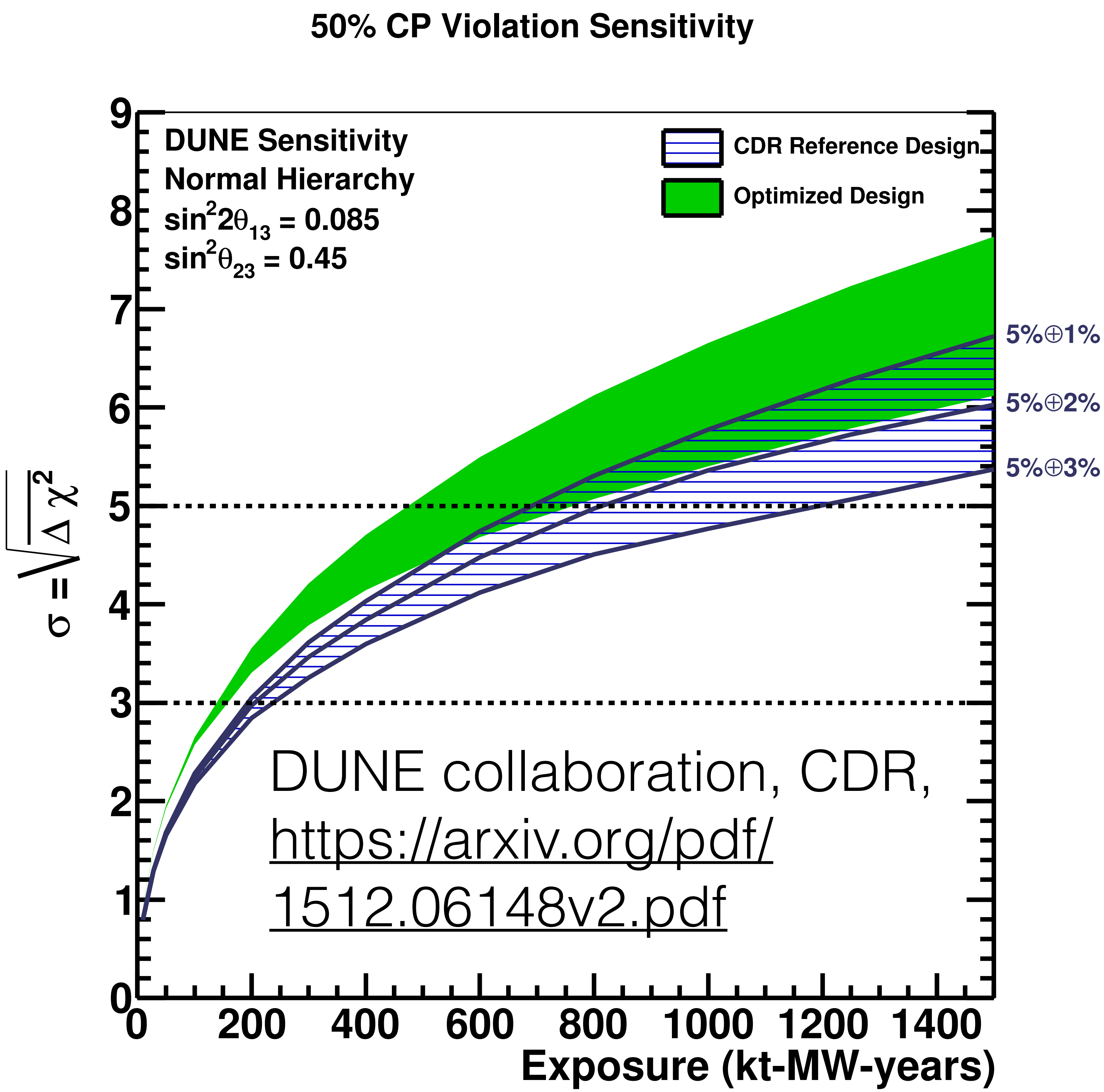
Studies on impact of alternate form factor

- Use as alternate models: "Z expansion", 3 component fit and perform T2K analysis with current dipole model (6 fits)
- For T2K 2018 analysis, the (Q^2) nuclear model parameters compensate for mis-modeling (no bias)



Will discuss next steps of this in a minute…

How well do we need to know ν-A?



DUNE collaboration, CDR, https://arxiv.org/pdf/1512.06148v2.pdf

- Examples shown for T2K are for current statistical uncertainty
- Problems only grow with reduced statistical uncertainty

Summary: the tool kit

- **Experimentalists may be the only ones to assess impact**
  - Significant considerations in detector acceptance and reconstruction effects
  - And incorporation of near detector information
- **Define interfaces:**
  - Low-level impact test: compare rate x expected uncertainty - comparable to our error budget (e.g. rare processes but highly uncertain?)
  - High level tests: Comparisons of parameterization and error envelopes, full ‘fake data studies’ where model is believed to be outside parameterization

How does neutrino interaction modeling affect oscillation analyses?

(subjective) ideas about how to move forward together

Sound Transit rendering of UW Station area

What do we need to move forward?
First, what is it we want?

- **Specific: Do we need updated information (theory or experiment or both) on single nucleon form factors?**

- **More broadly: How do we interface (external) information to experiments?**

    - How well do I need to know X theoretical effect? Was Y approximation sufficient?

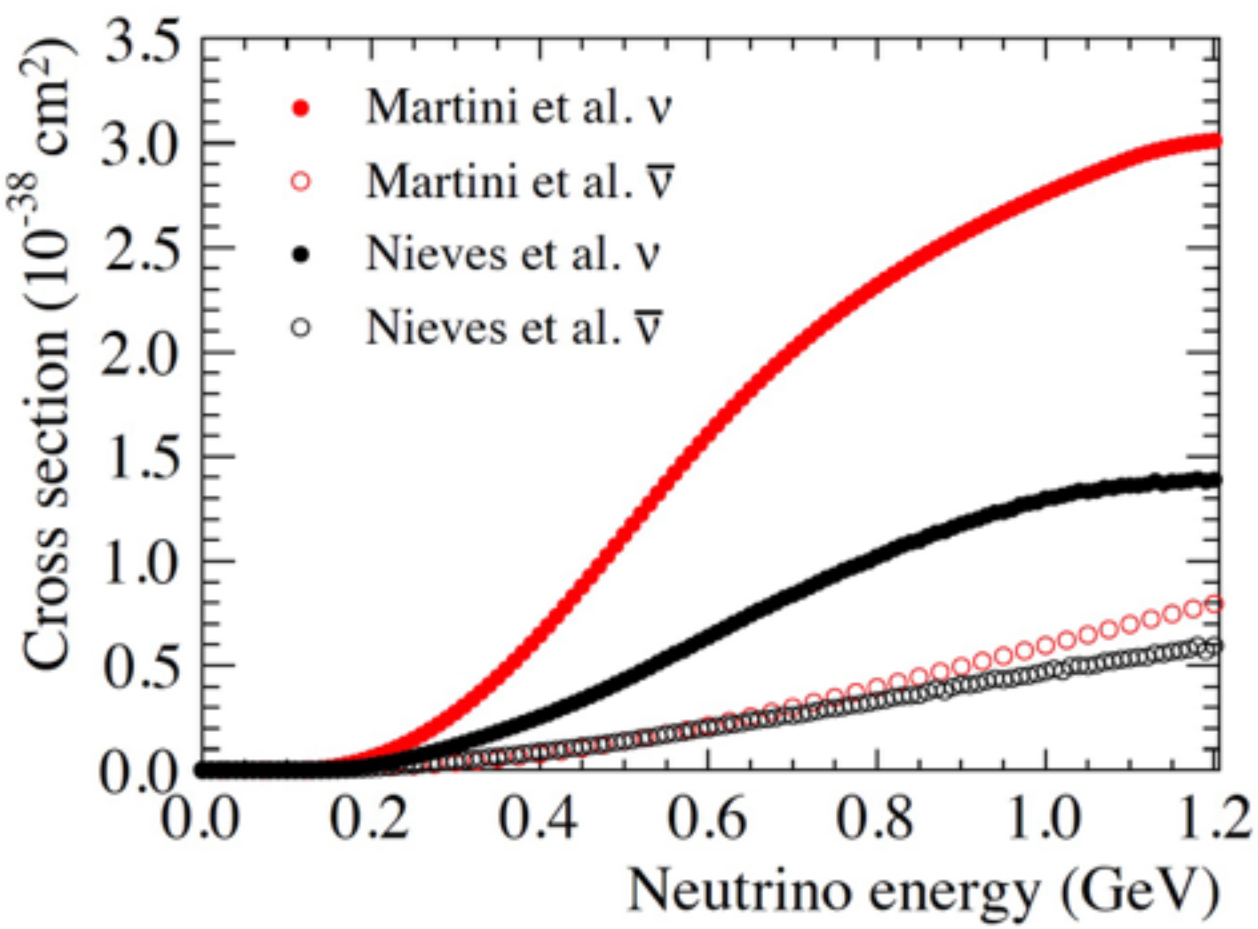
    - What is the role of electron scattering?

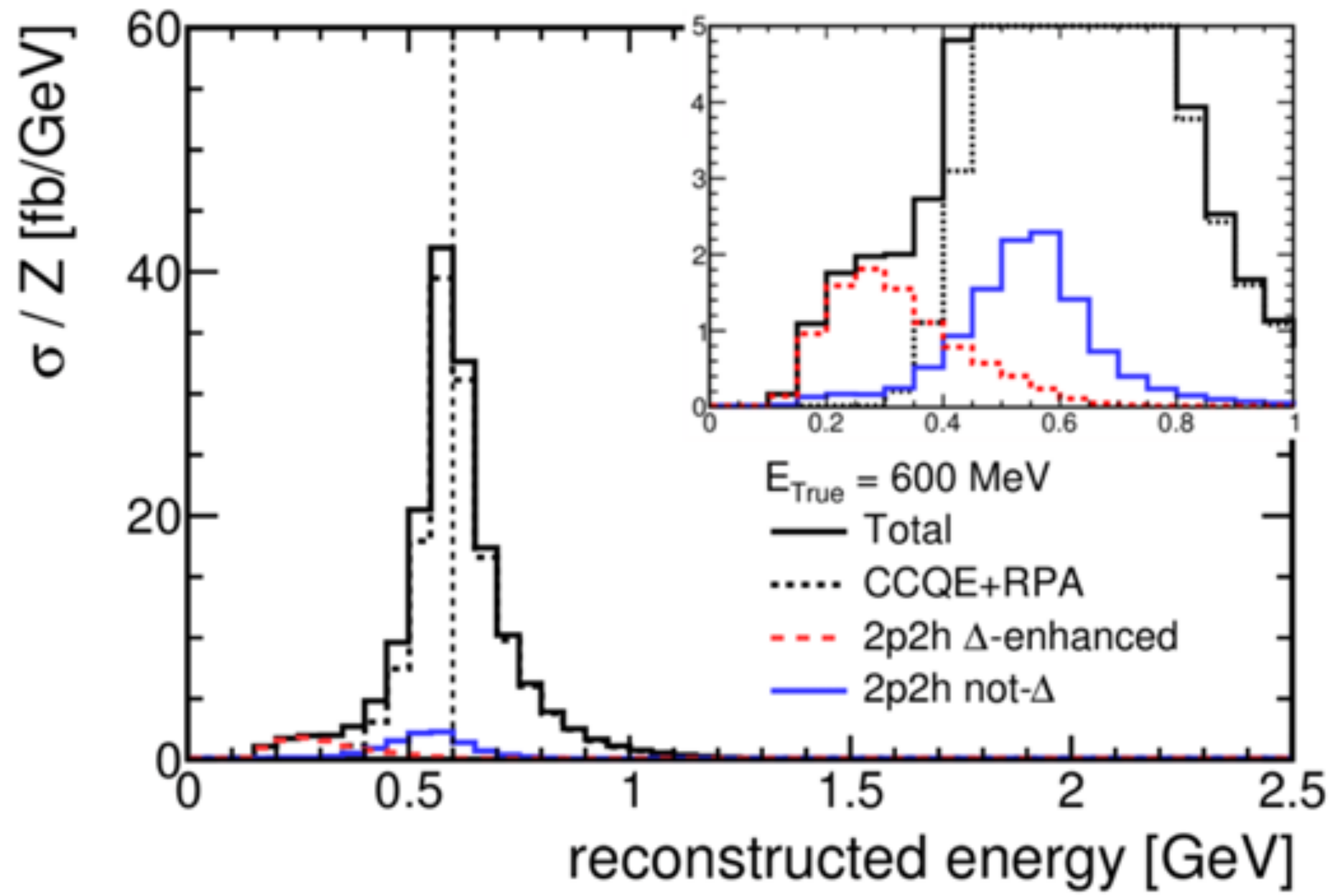
(Nuclear model) questions about QE+2p2h

- Multiple processes “stack” in observables; need uncertainties on all aspects
  - A data disagreement assuming QE energy dependance has a different effect in the T2K analysis than one with 2p2h energy dependance

(Nuclear model) questions about QE+2p2h

- Multiple processes "stack" in observables; need uncertainties on all aspects
- What is the energy dependance of 2p2h? Between models? And neutrino scattering measurements?

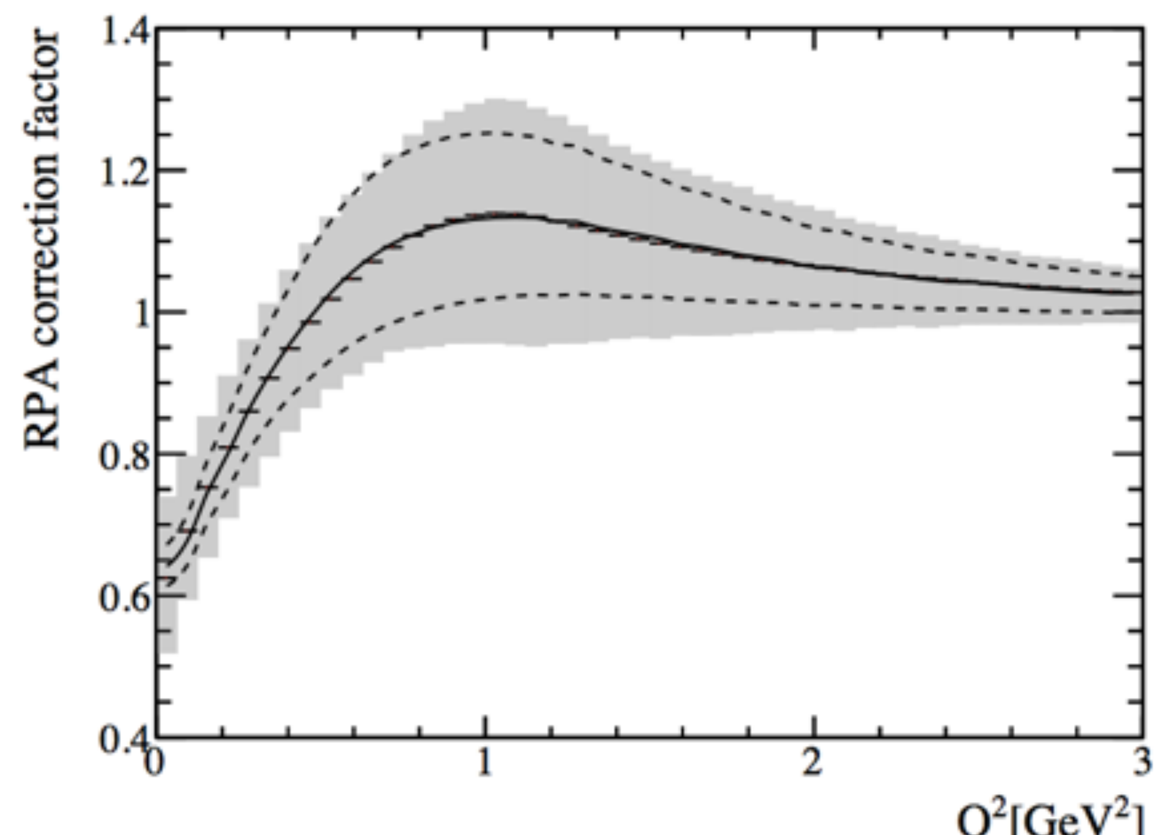




PRD 96, 092006 (2017)

(Nuclear model) questions about QE+2p2h

- Multiple processes "stack" in observables; need uncertainties on all aspects
- What is the energy dependance of 2p2h? Between models? And neutrino scattering measurements?
- What does the cross section do at high Q^2?
  - Nuclear model and (single nucleon) axial form factor dipole or not?



What is the role of single nucleon form factors in oscillation experiments?

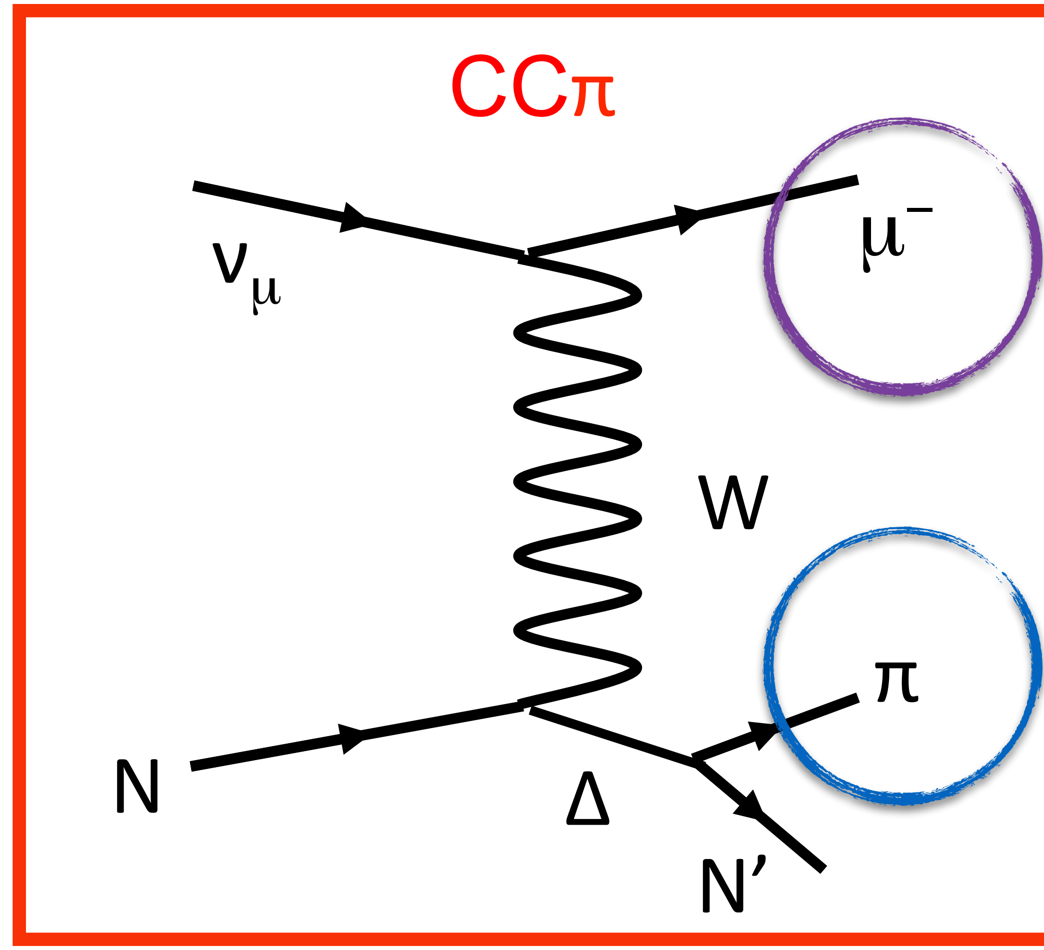
- **From T2K:**
  - How much 2p2h you include depends on 1p1h ingredients, including the form factor & energy dependance.
  - But, current issues are (nuclear) uncertainties on 2p2h (or energy dependance of 1p1h).
  - Acceptance at ND and FD is often different as well

What is the role of single nucleon form factors in oscillation experiments?

- **Suggestions for QE single nucleon form factors:**
  - 1) axial vector ~~mass~~ form factor at O(5%) - *we can compare to what we currently assume*
  - 2) possible deviation from dipole assumption
  - Updated fake data study with high statistics

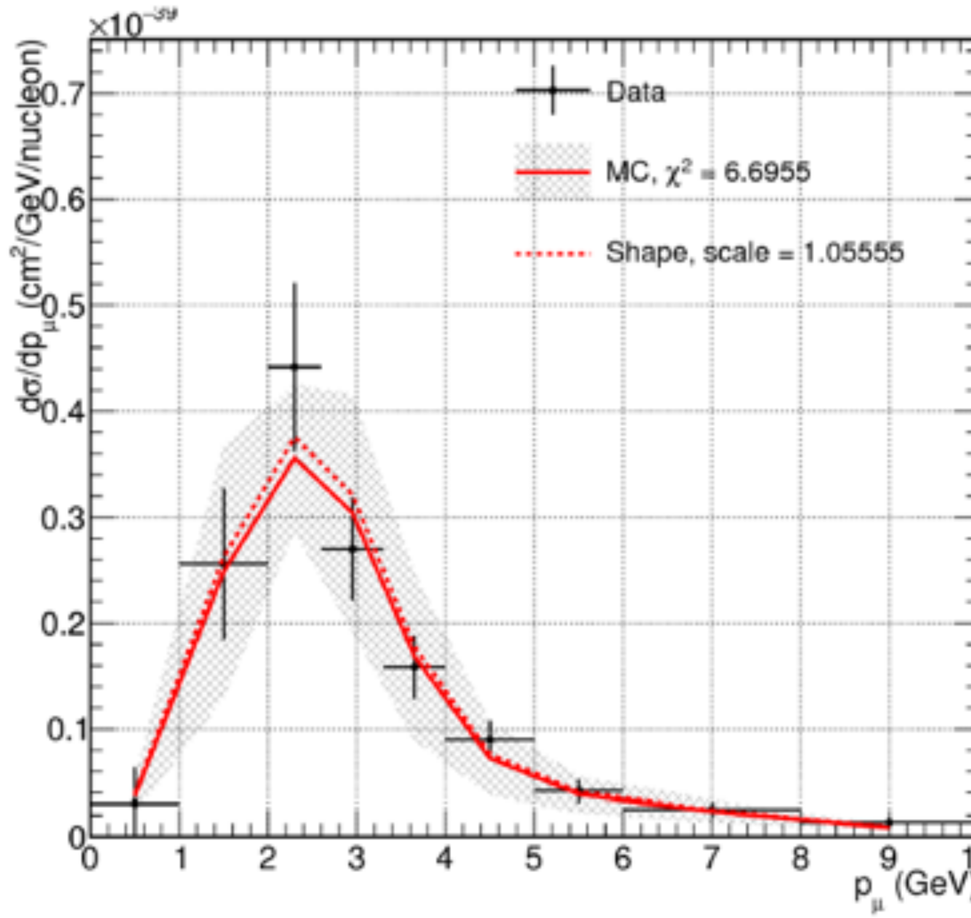
What is the role of single nucleon form factors in oscillation experiments?

- Important background (and signal) process for oscillation (non-standard) physics
- **Challenge to model!**
  - non-resonant backgrounds?
  - pion re-interaction (final state interaction) model?
  - **Busted single nucleon model?**
- Example from NUISANCE software framework thanks to C. Wilkinson - *Dec 2016 seminar:* http://npc.fnal.gov/neutrino-seminar-series/2016-2017-season/



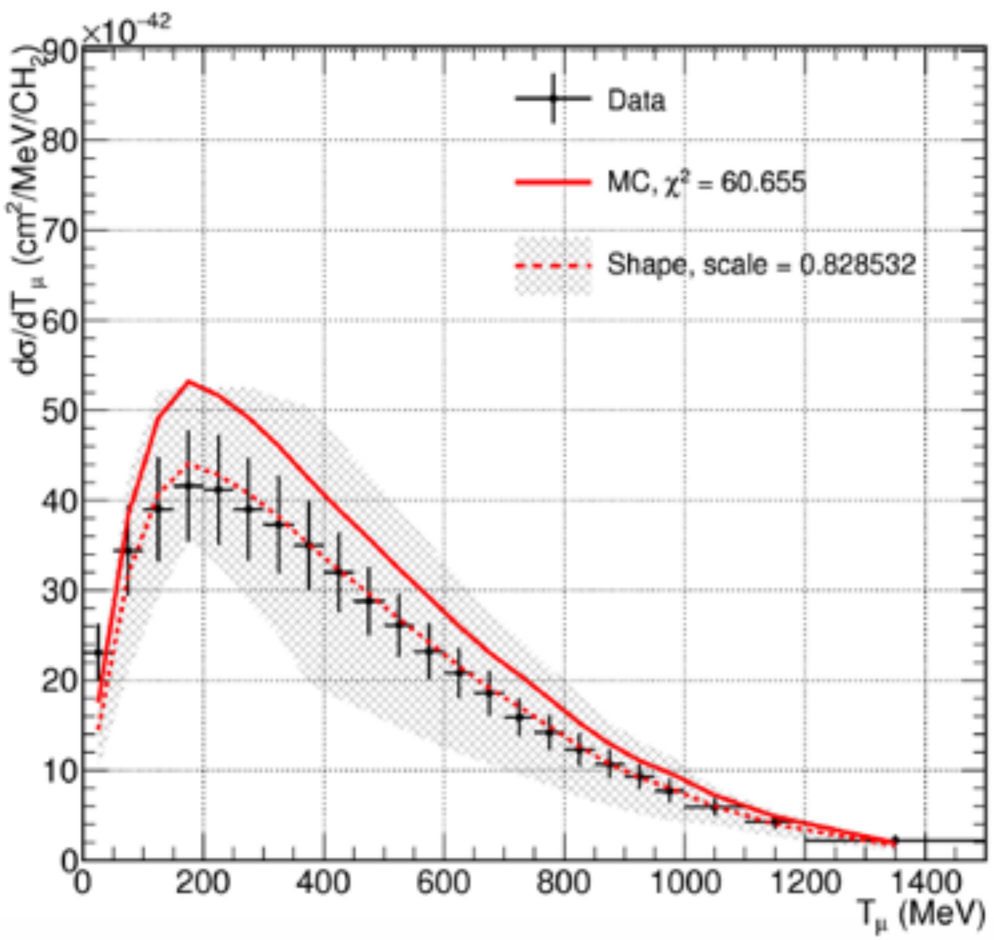
Single Pion Production Puzzles

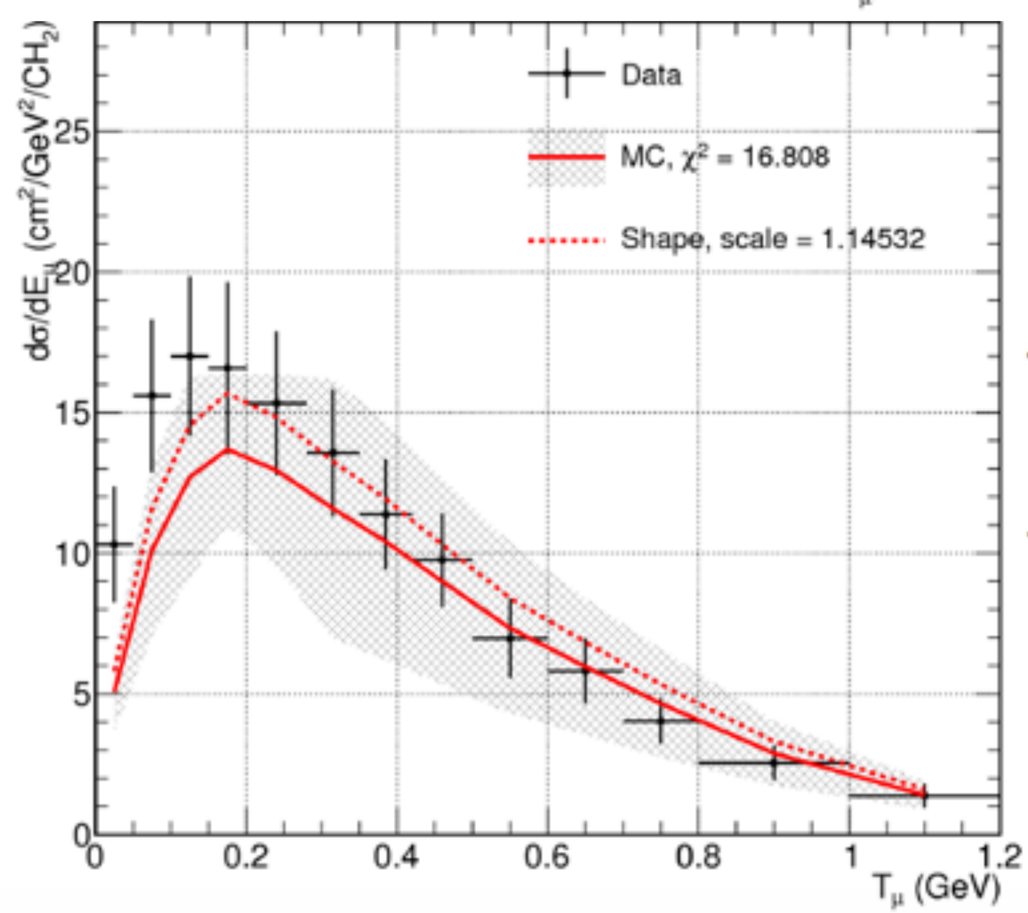
- **Reasonable agreement in outgoing muon spectrum**
- Terrible agreement in outgoing pion spectrum
- Model development essential



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005

MB ν_μ-CH_2 CC1π^+
PRD 83 (2011) 052007





MB ν_μ-CH_2 CC1π^0
PRD 83 (2011) 052009

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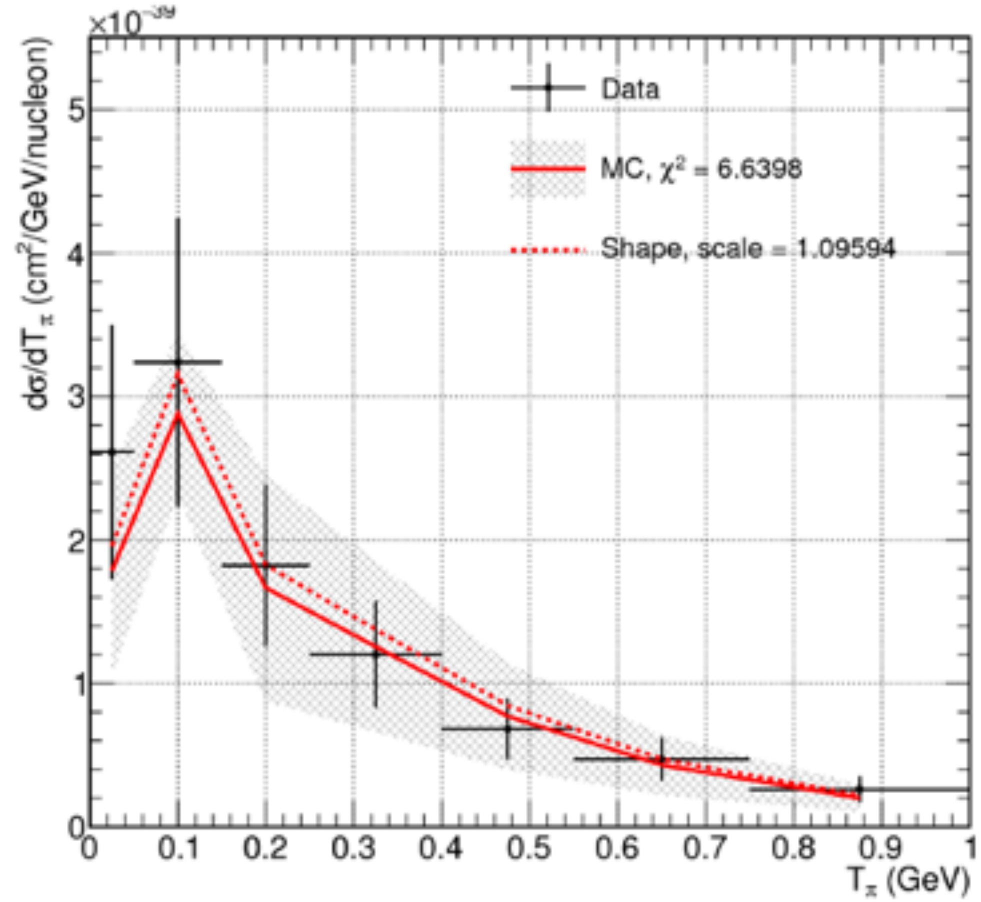

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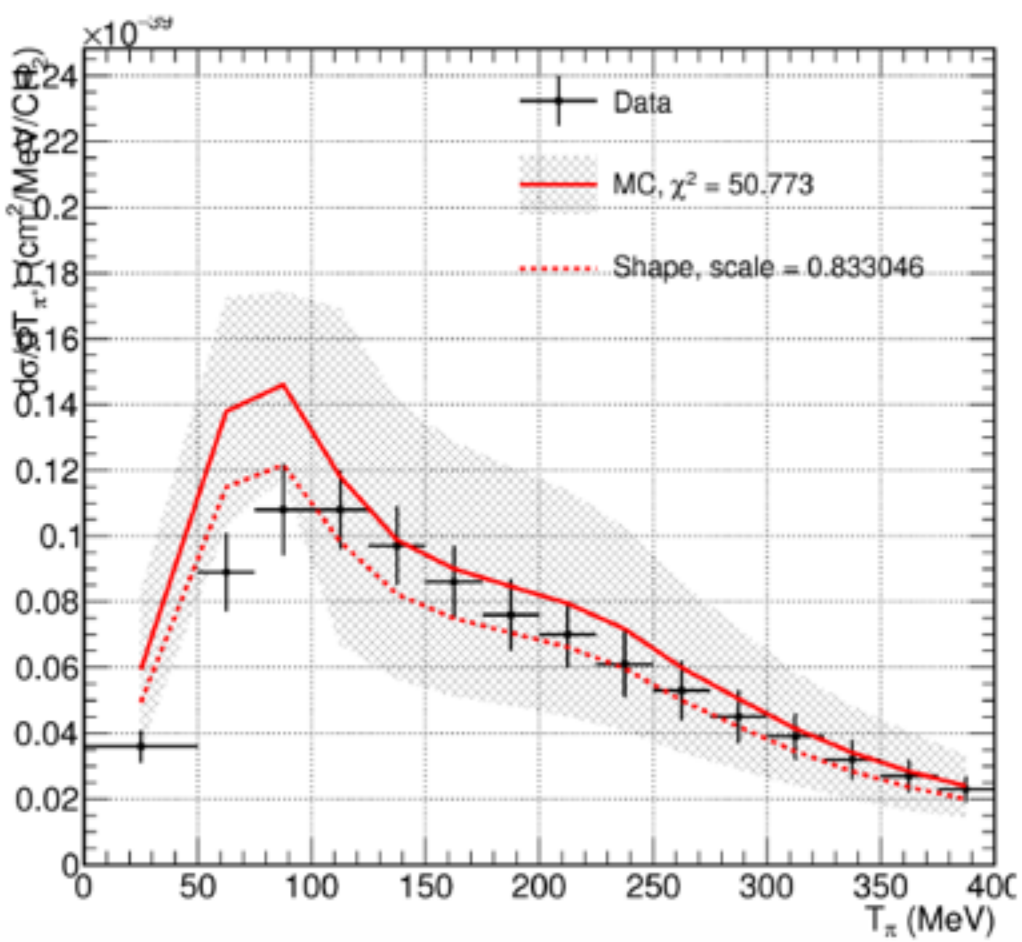

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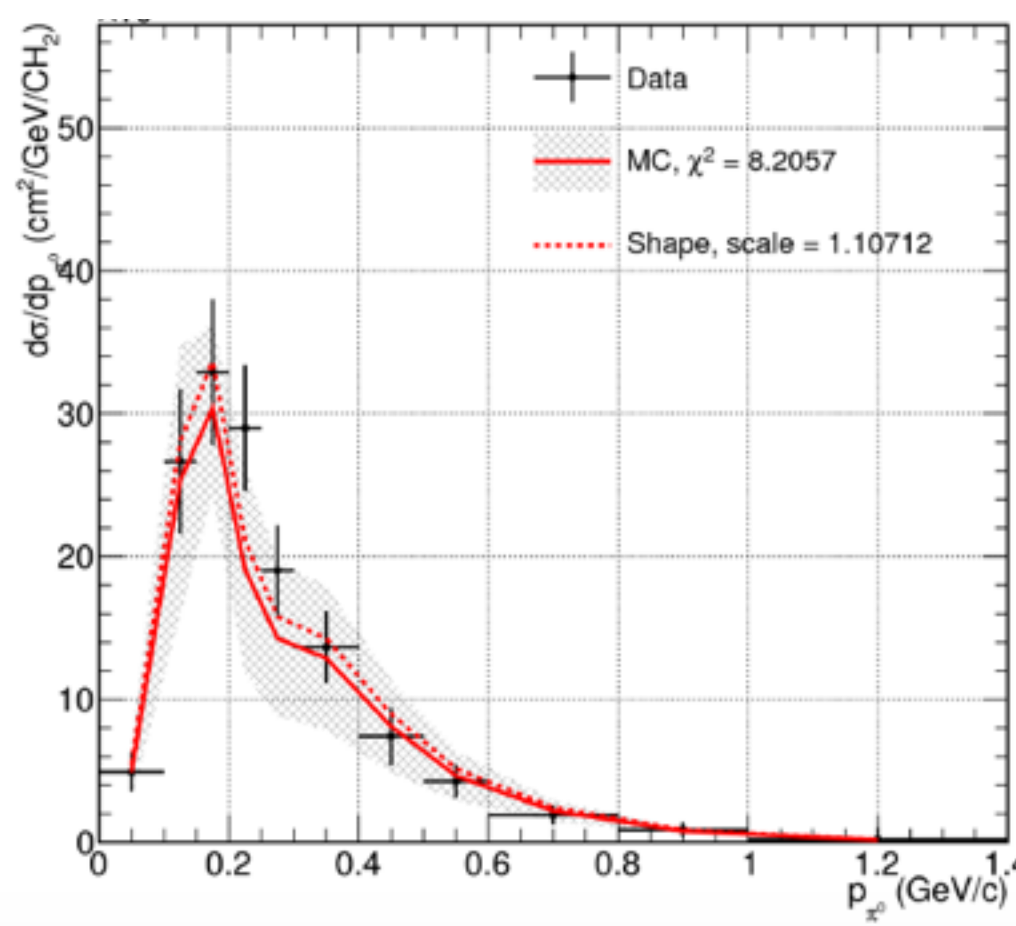
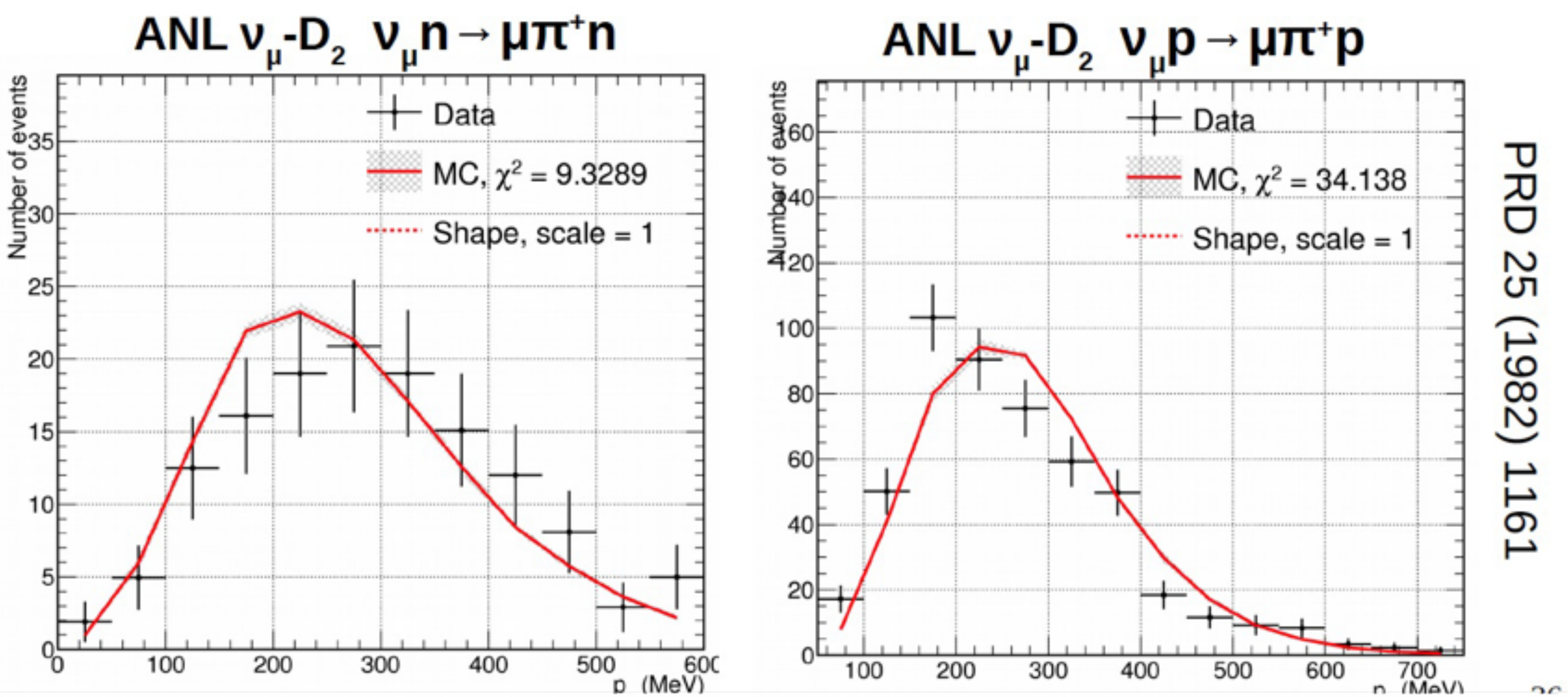


MB ν_μ-CH_2 CC1π^0
PRD 83 (2011) 052009

Single Pion Production Puzzles

- Very little flexibility in the interaction model to change the pion kinematics.
- Agreement with ANL data not amazing. More work required before moving onto FSI uncertainties/ nuclear effects.

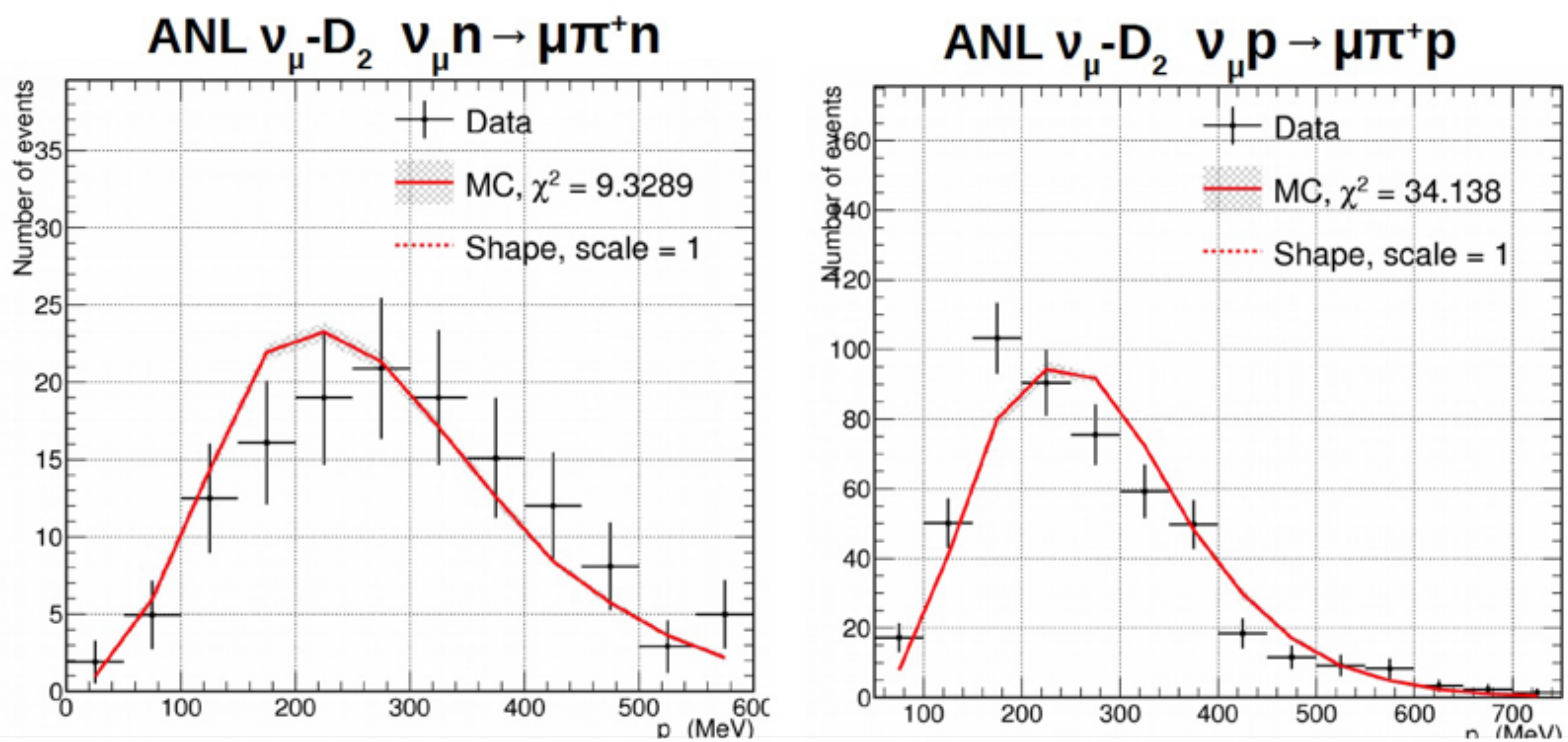


PRD 25 (1982) 1161

What should be the model uncertainty?
Especially: pion kinematics?

Single Pion Production Puzzles

- Very little flexibility in the interaction model to change the pion kinematics.
- Agreement with ANL data not amazing. More work required before moving onto FSI uncertainties/ nuclear effects.



PRD 25 (1982) 1161

How do we deal with disagreement?
When is a new experiment needed?

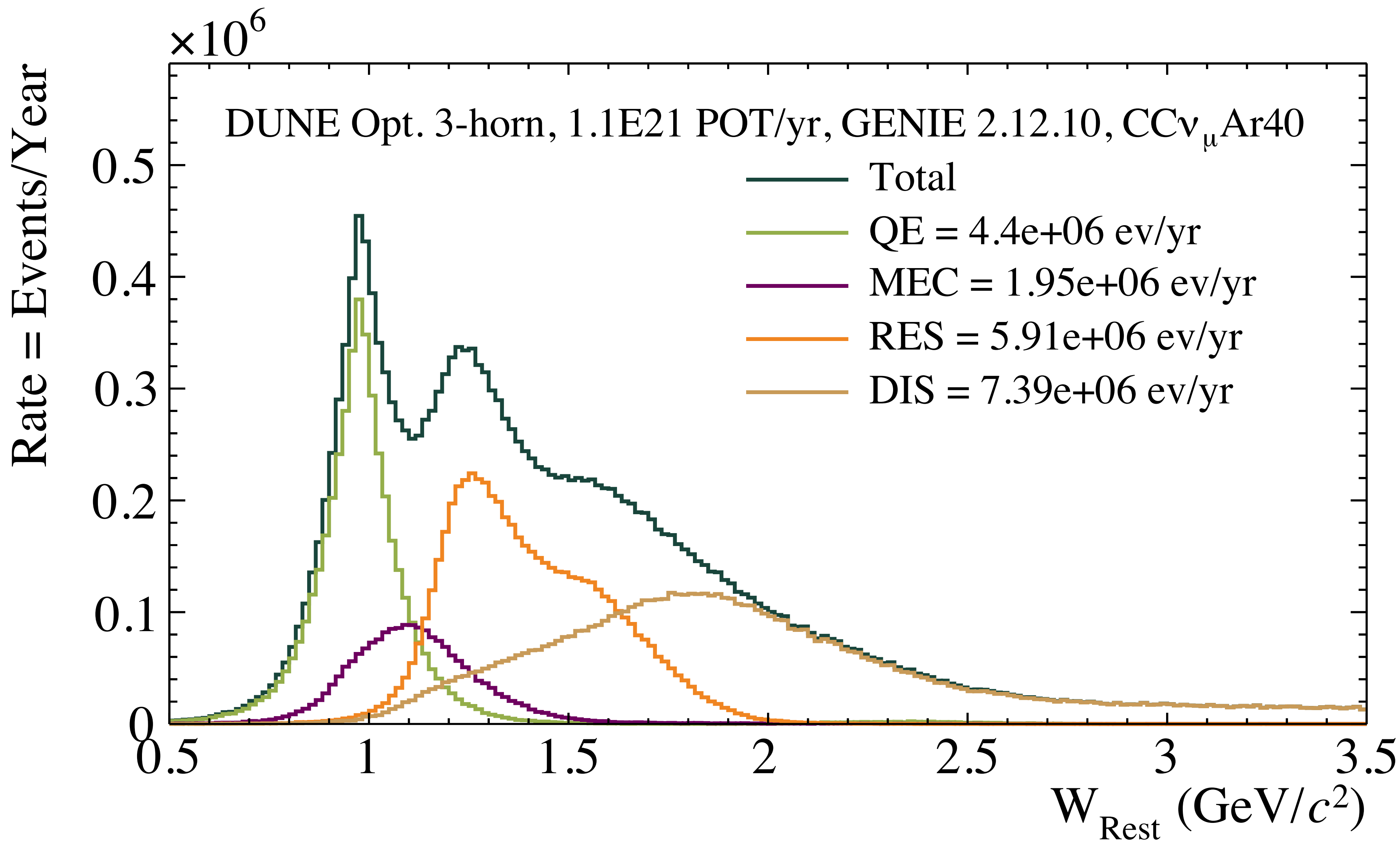
What is the role of single nucleon form factors in oscillation experiments?

- **We need to start understanding what can be done to better understand sufficiency in resonance production.**
- Progress needed on parameterizing and propagating difference between available resonance production models and available data.
- **Q: What are the interfaces?**

What is the role of single nucleon form factors in oscillation experiments?

- **Transition region - critical for DUNE**

- Presumably this is a necessary input?



Other (theory, experiment) interfaces

- **How bad are our approximations? Uncertainty quantification**
  - Previous QE/2p2h questions, single pion production
  - Projections of modern theory against generators in NUISANCE - w/ G. King, F. Nunes (MSU) based on discussion S. Pastore (LANL), next page
  - Sources of (NC) single photons - very hard to access experimentally
  - Electron scattering is critical for hadronic state simulation - *see Adi's talk*
- **Define interfaces:** between groups? a master parameterization?

MSU mini-theory+experiment idea

Lovato, Gandolfi et al, PRC97 (2018) no.2, 022502

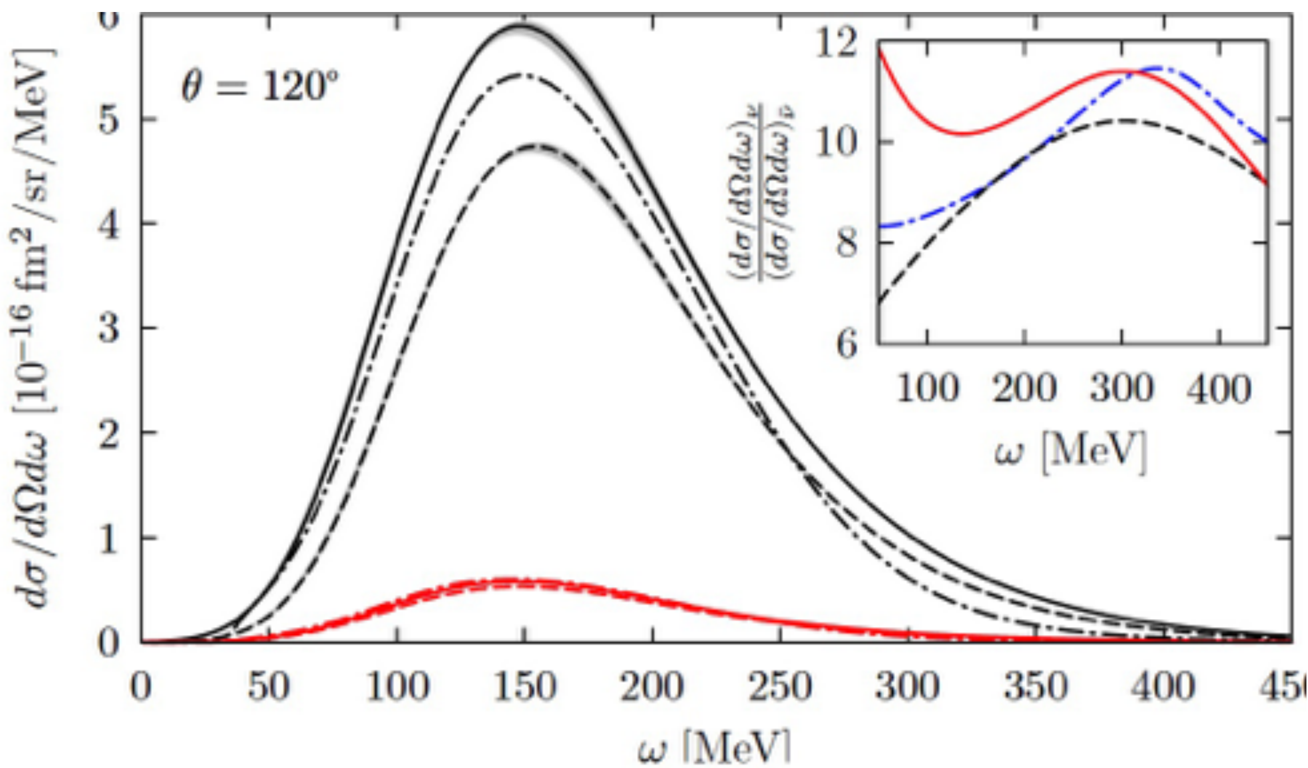
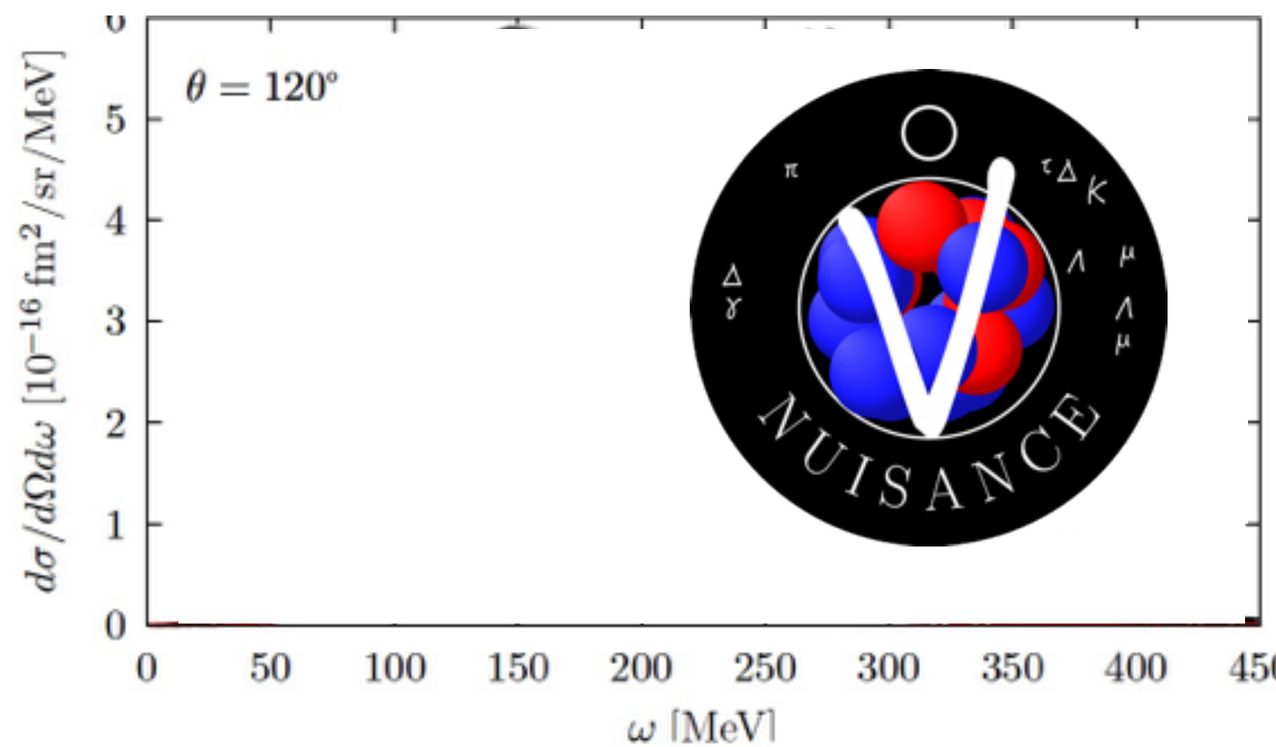


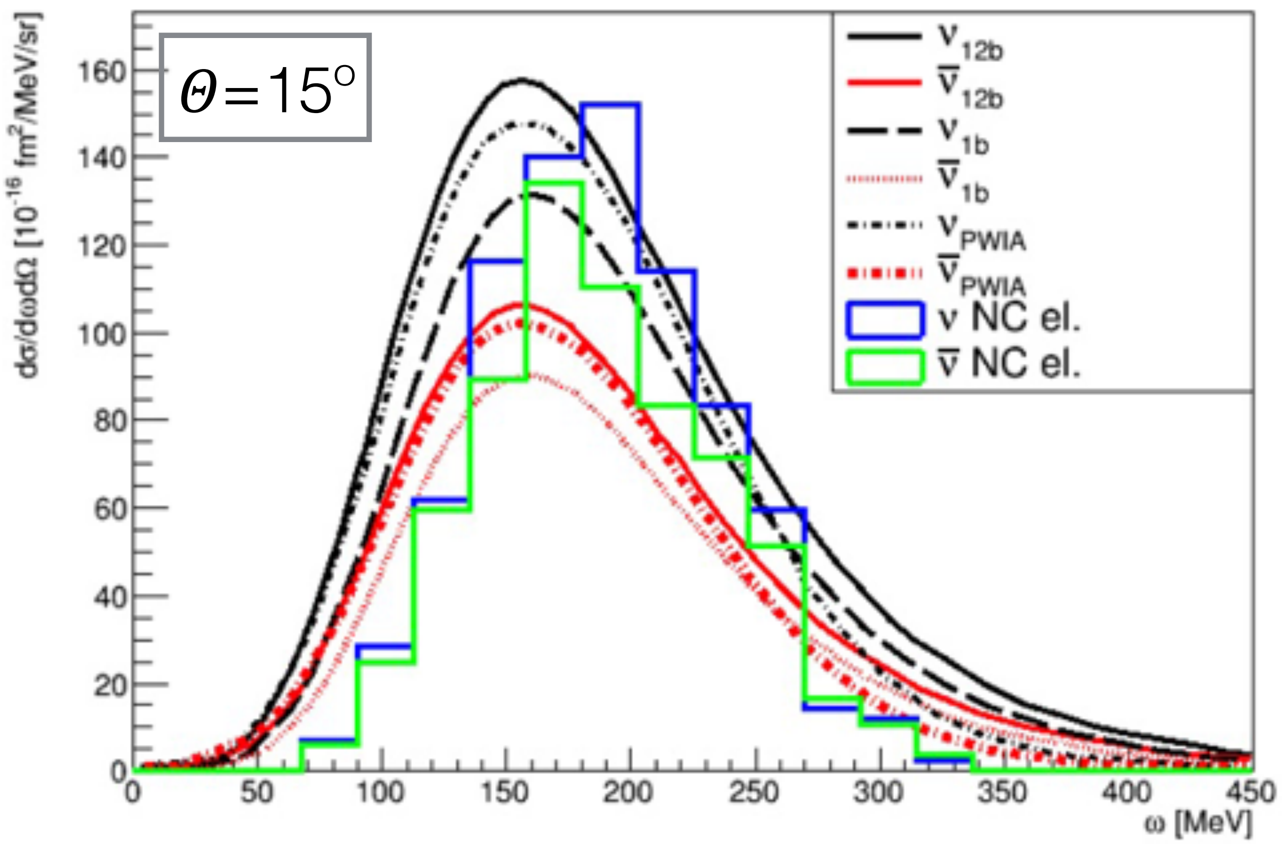
FIG. 2. (Color online) Weak neutral ν (black curves) and $\overline{\nu}$ (red curves) differential cross sections in ^{12}C at $q=570$ MeV/c, obtained with one-body only and one- and two-body terms in the *NC*. The final neutrino angle is indicated in each panel. The insets show ratios of the ν to $\overline{\nu}$ (central-value) cross sections. Also shown are the PWIA results.

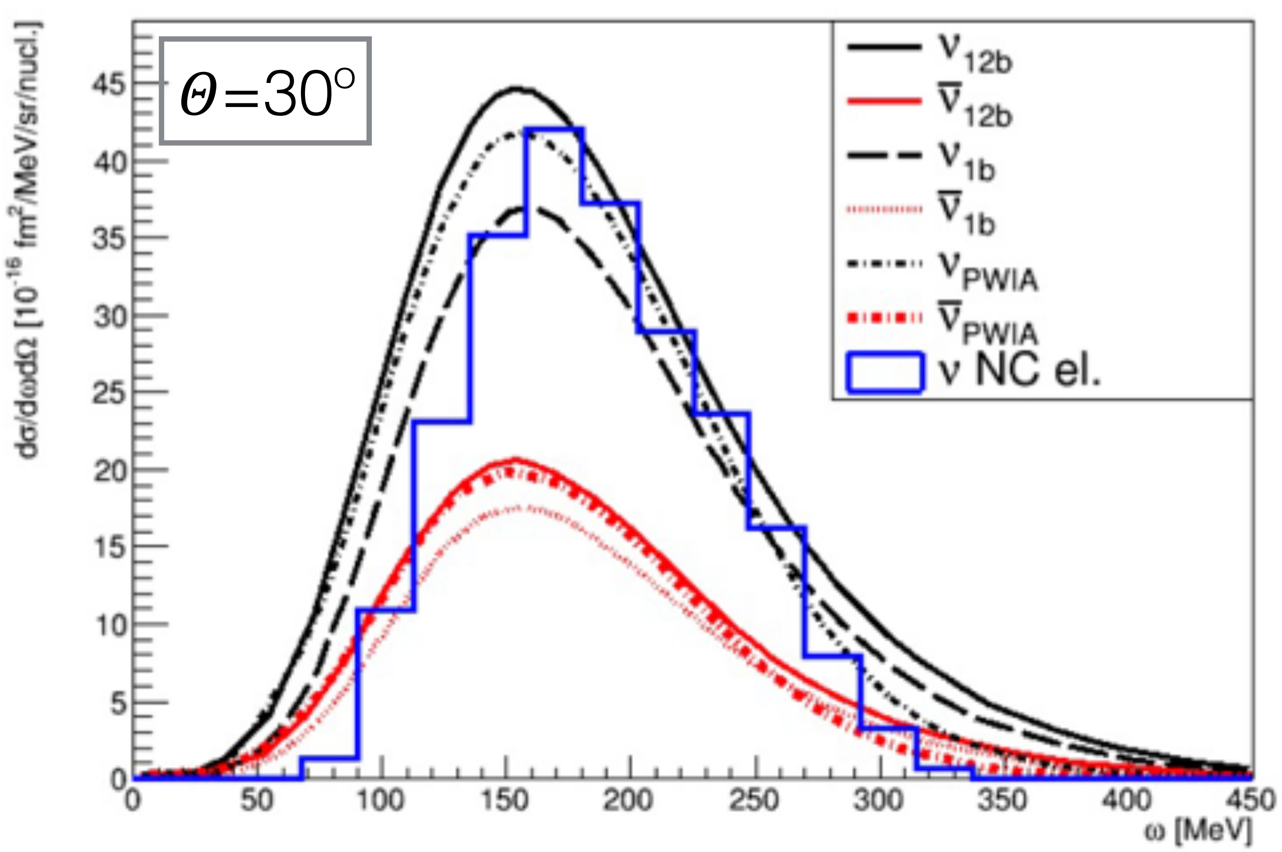


- Prepare GENIE generator for NC @570 MeV

- Goals: 1) Establish common language and useful (theory) projections 2) What are the (missing) features in generators? 3) (future) What is the impact of what is missing?

MSU mini-theory+experiment idea





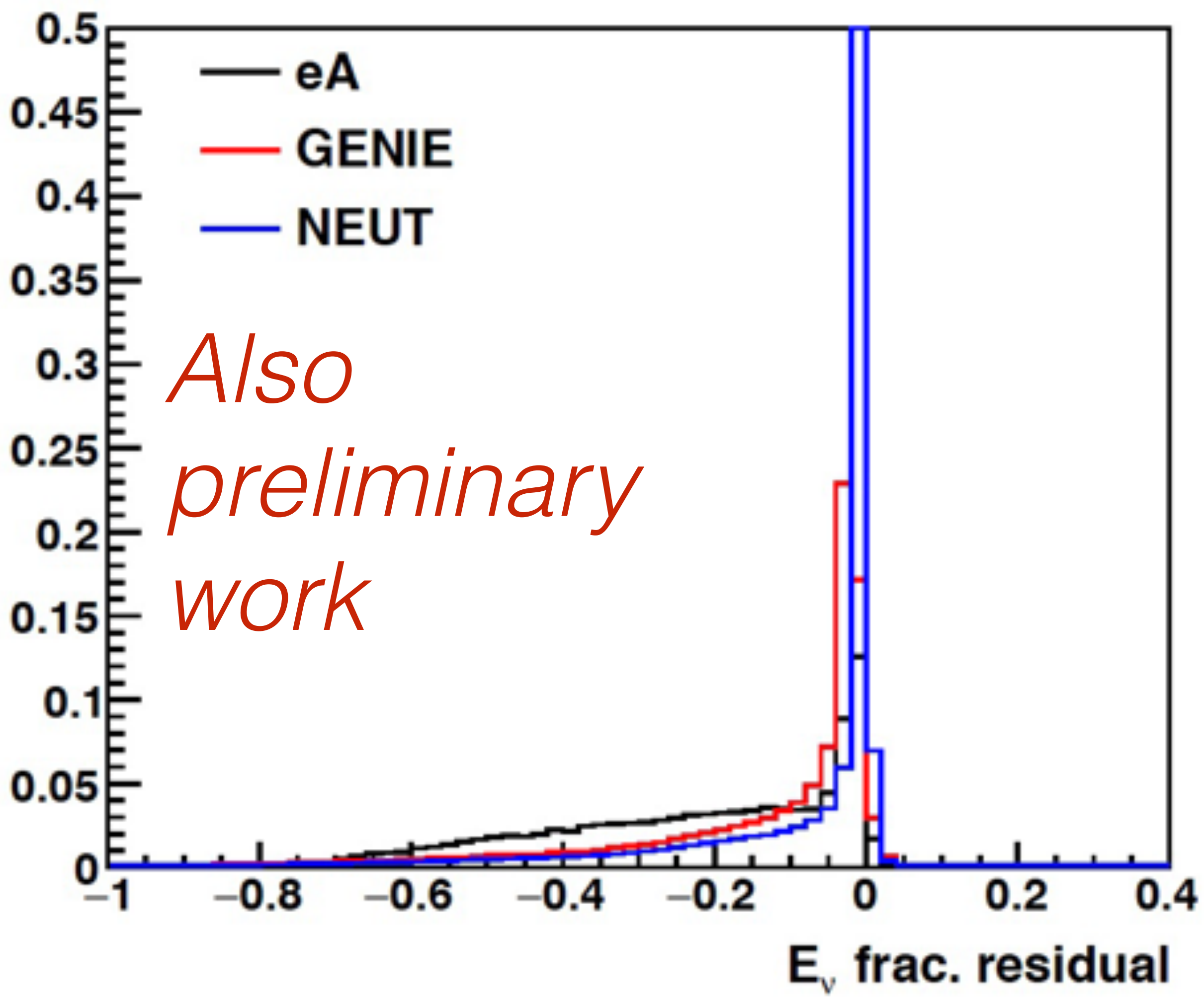
extremely preliminary work…

(**within the generator**) Do disagreements produce appreciable event rate differences for kinematics of interest?

(**within the theory**) What physics is the model including?

What does inclusive do to inform (semi exclusive, exclusive) models?

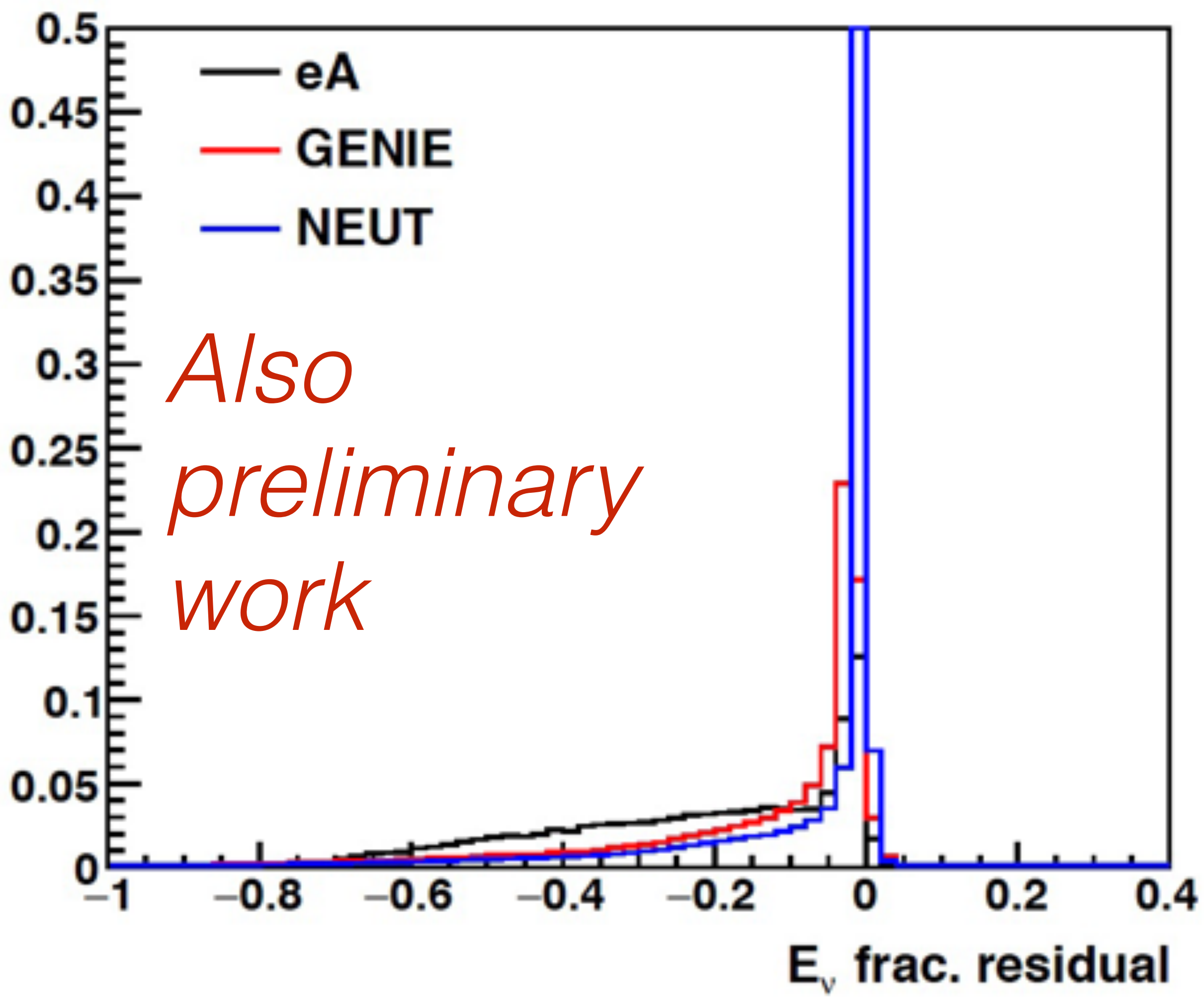
Electron scattering connection
How bad are our approximations?



See Adi's talk - collaboration of Or Hen, Larry Weinstein, Afroditi Papadopoulou ,Mariana Khachatryan, Luke Pickering, Adrian Silva, Axel

- Comparison of (2.2 GeV, fixed energy) electron scattering data (corrected for Mott xsec) against neutrino simulations; acceptance corrections included. CC0pi signal.
- Electron scattering data (broad acceptance) tests particle multiplicity and kinematics through energy estimator

Electron scattering connection
How bad are our approximations?



Interface success? -core projection of response function assumed in osc analysis

- Comparison of (2.2 GeV, fixed energy) electron scattering data … corrections included. CC0pi signal.

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

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Electron scattering connection

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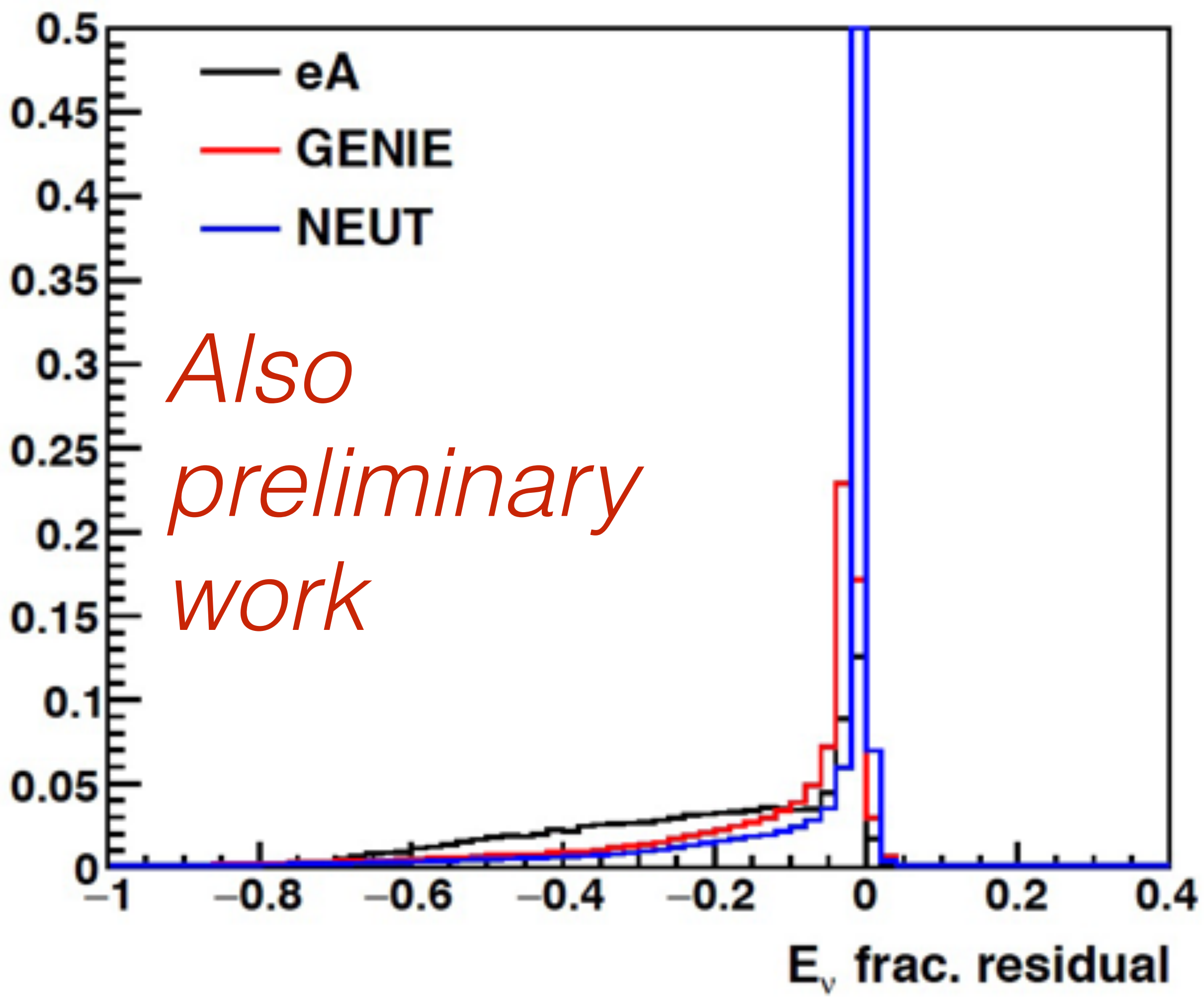

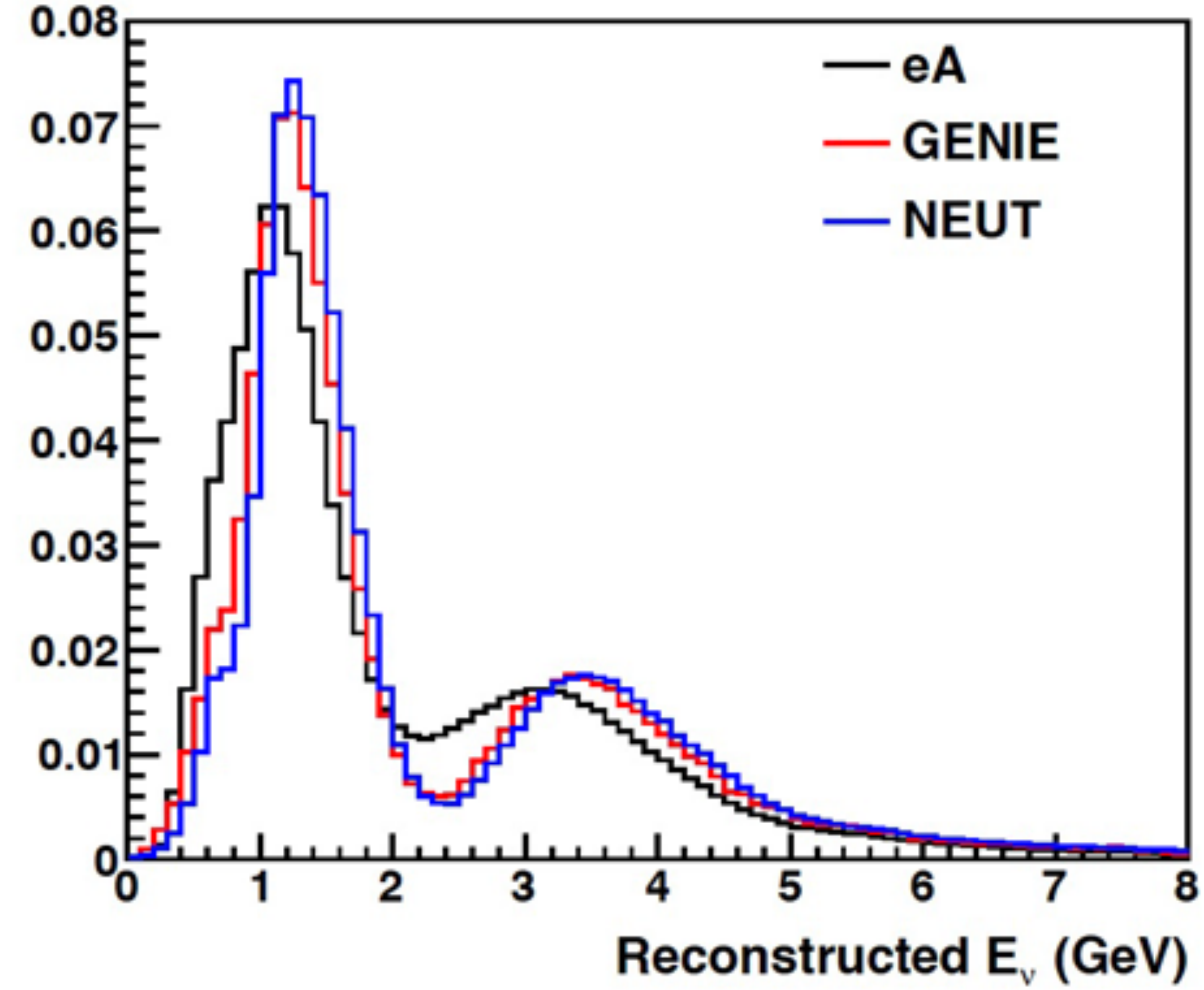

- DUNE oscillated flux; apply fractional feed down adjustment to nearby energies

- Next work: revisit assumptions in each step (equivalence of electron-neutrino, scaling with energy)

Closing thoughts

- **Current and future neutrino oscillation program critically depends on theory inputs from nuclear, high energy communities**
  - To avoid bias in our results
  - To assign correct, robust uncertainties

Closing thoughts

- **Current and future neutrino oscillation program critically depends on theory inputs from nuclear, high energy communities**

  - To avoid bias in our results

  - To assign correct, robust uncertainties

Not everyone agrees. We have to try to achieve consensus among various community stakeholders (experimentalists, theory groups) that this is important.

Closing thoughts

- Current and future neutrino oscillation program critically depends on theory inputs from nuclear, high energy communities

- **It's a complex problem due to role of near detector, incomplete models and approximations**

  - What is useful information (in error budgets, parameterizations) for external groups to understand the current status and do initial estimates? - **establish interface** from osc to inputs

  - Probably, full studies of impact must be done by experiments. What can be done to ease this process?

Closing thoughts

- Current and future neutrino oscillation program critically depends on theory inputs from nuclear, high energy communities
- It’s a complex problem due to role of near detector, incomplete models and approximations
- **Where can we bridge the gap here?**
  - Where do we see evidence for incomplete models? Identify it, and quantify the impact.
  - Propagate improvements to quantities (observables, intermediate quantities) for experimental impact estimation and comparison

Closing thoughts

Thank you for the invitation, let's go on a walk together