Neutrino interaction uncertainties in current (T2K) and future (T2HK) experiments

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Thank you for the generous support,
it is wonderful to be here.

Disclaimers

This talk is largely my personal view and understanding; I am not here formally for T2K nor T2HK. T2K and HK collaborators, feel free to comment and I will adjust accordingly.

My goal is to be as transparent and clear as possible, but I may use a lot of experimental jargon or imprecise language. Let me know if I am unclear.

I also speak very quickly… feel free to ask me to slow down or repeat!

What are the relevant features of T2K for generators and theory?

What are the current uncertainties are assigned to generators/theory for T2K analyses?

What are open questions/current lines of study?

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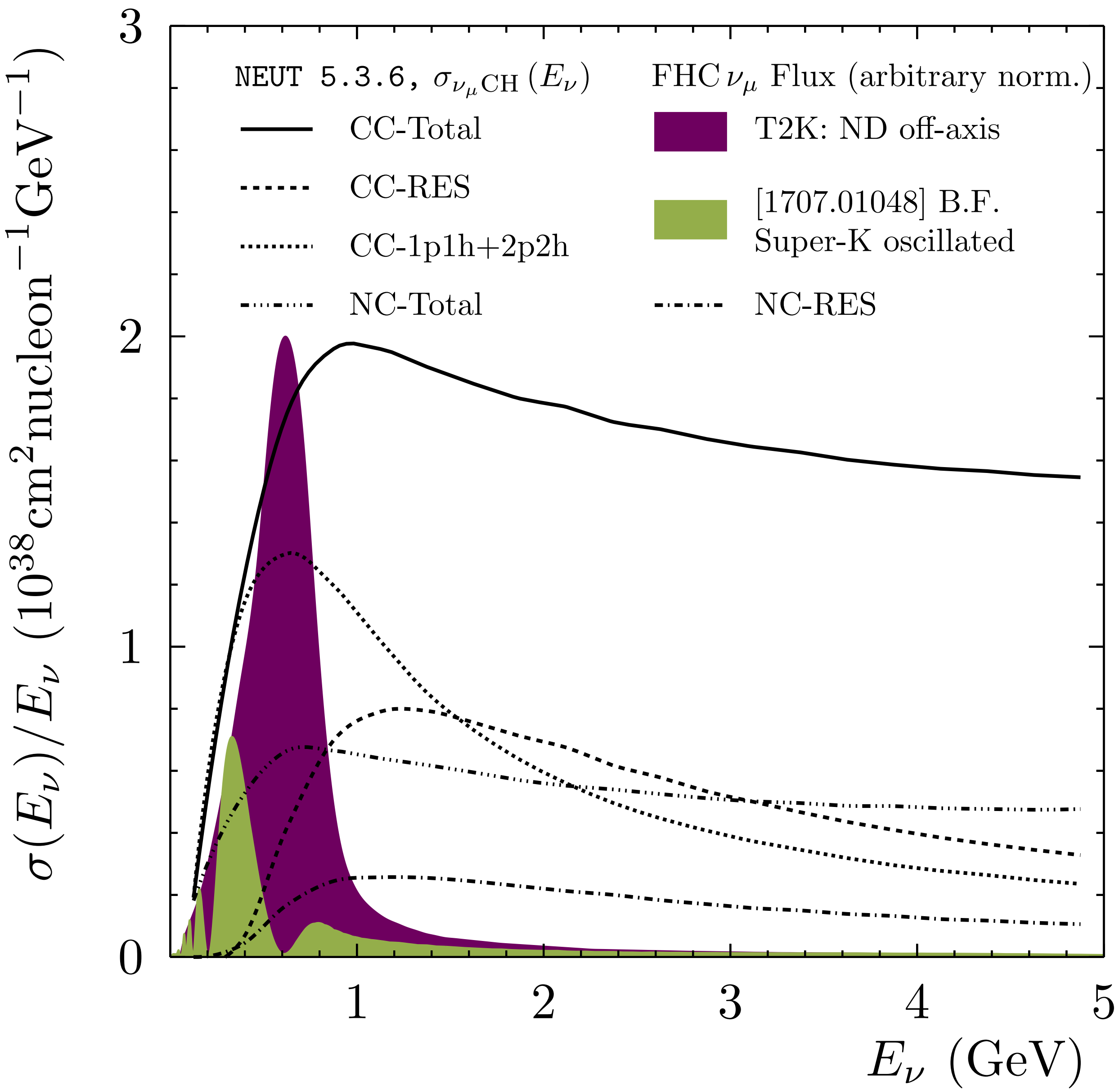
What are open questions/current lines of study?

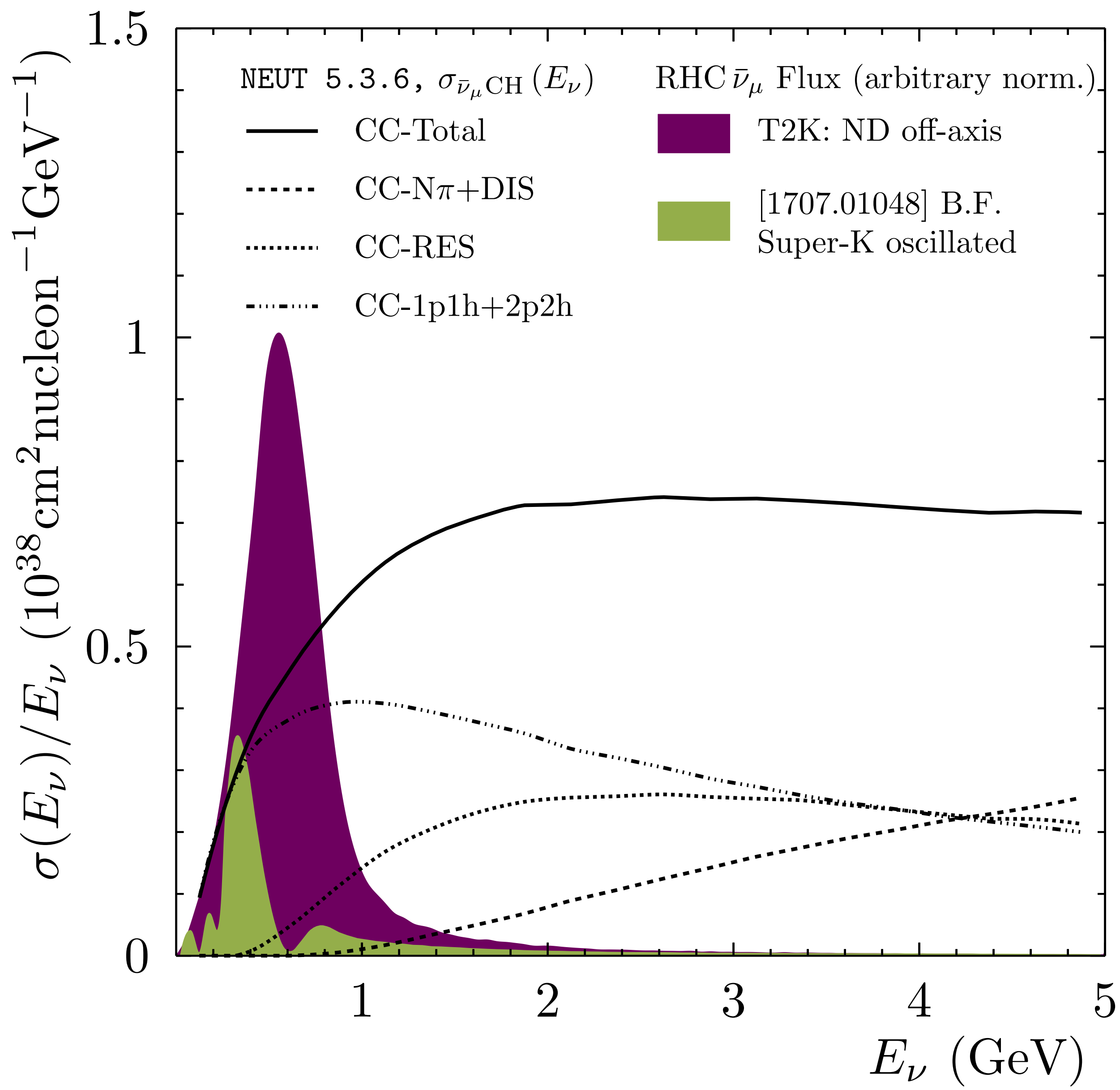
Inputs communities:
Nuclear theory
HEP theory
Electron scattering
Neutrino scattering

Oscillation analyses

What are the relevant features of T2K for generators and theory?

First, the neutrino sources





- 2.5 deg off-axis spectra (above): electron, muon + antineutrinos (right)

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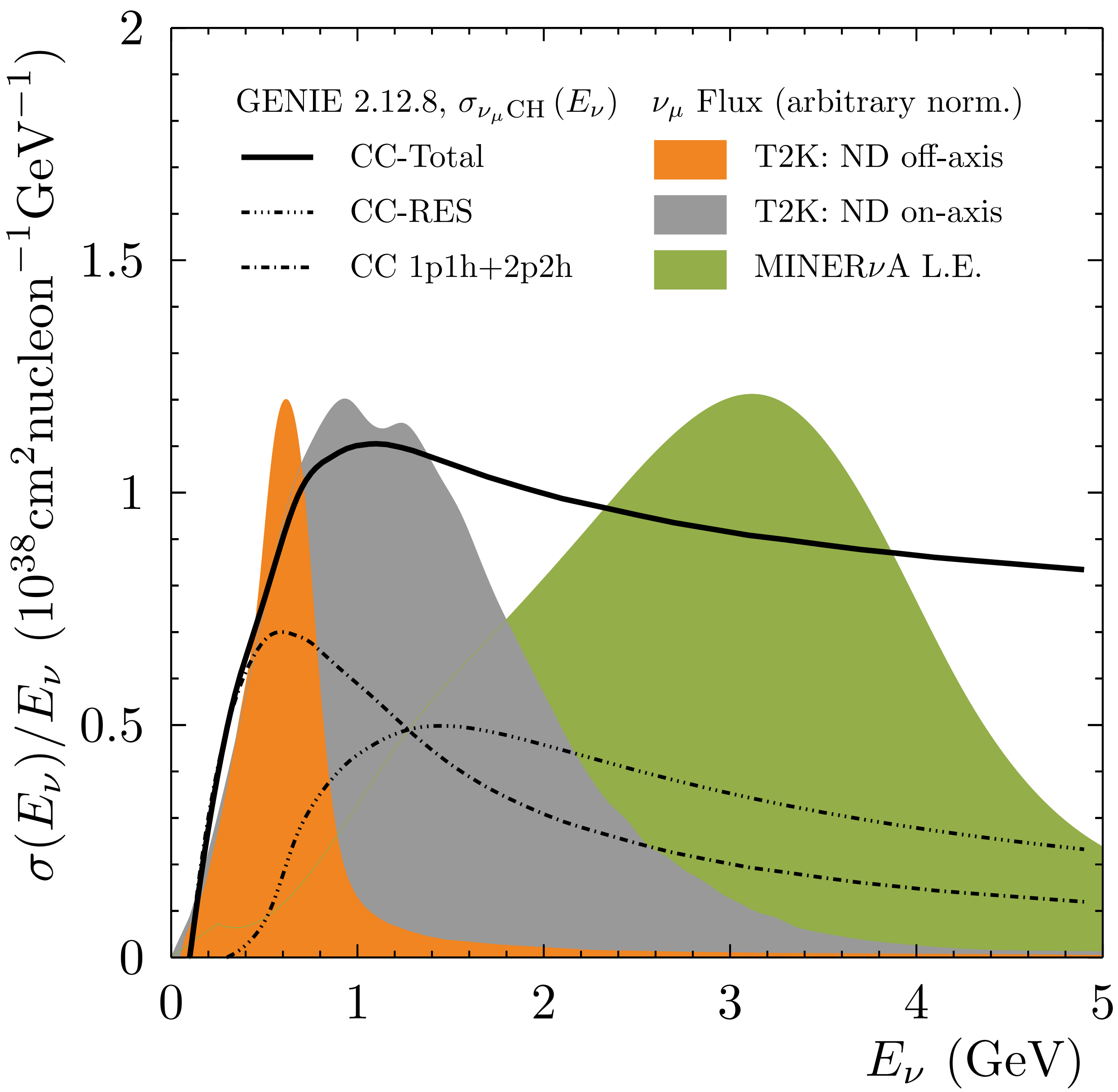
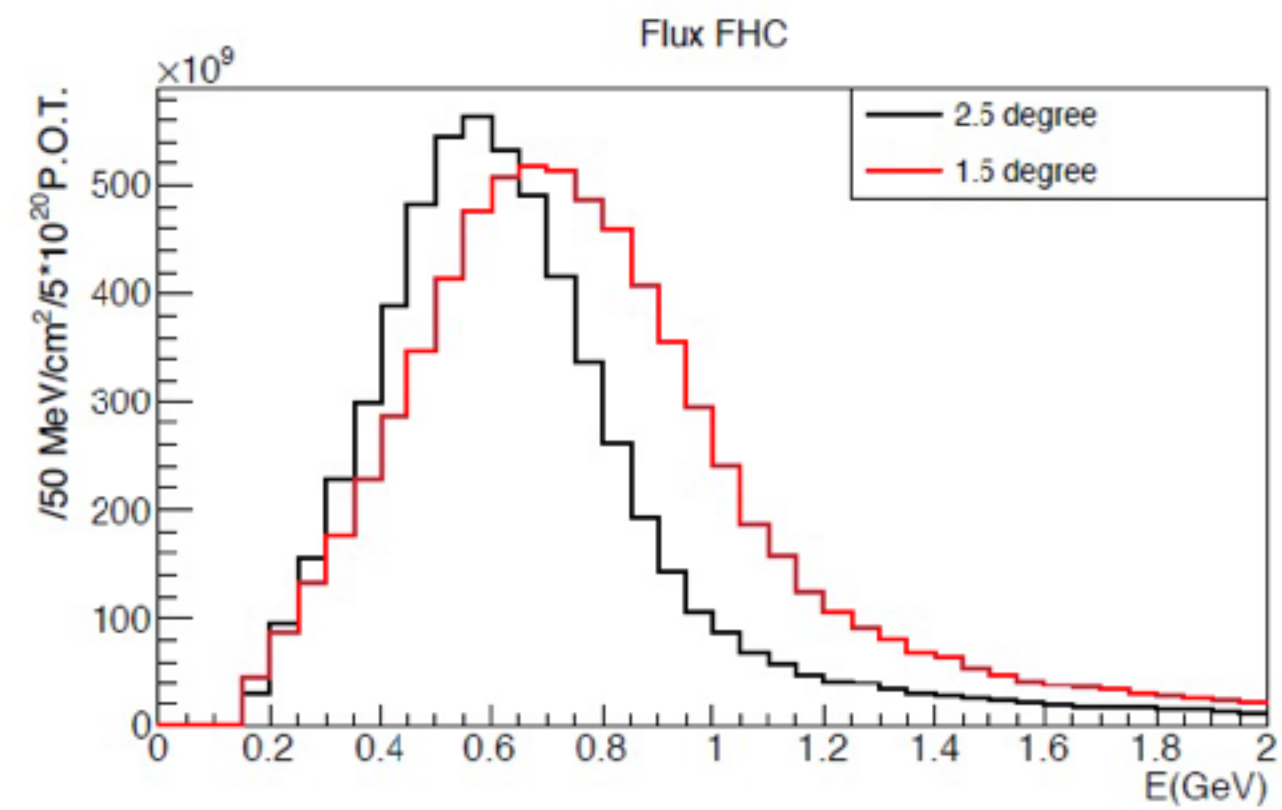
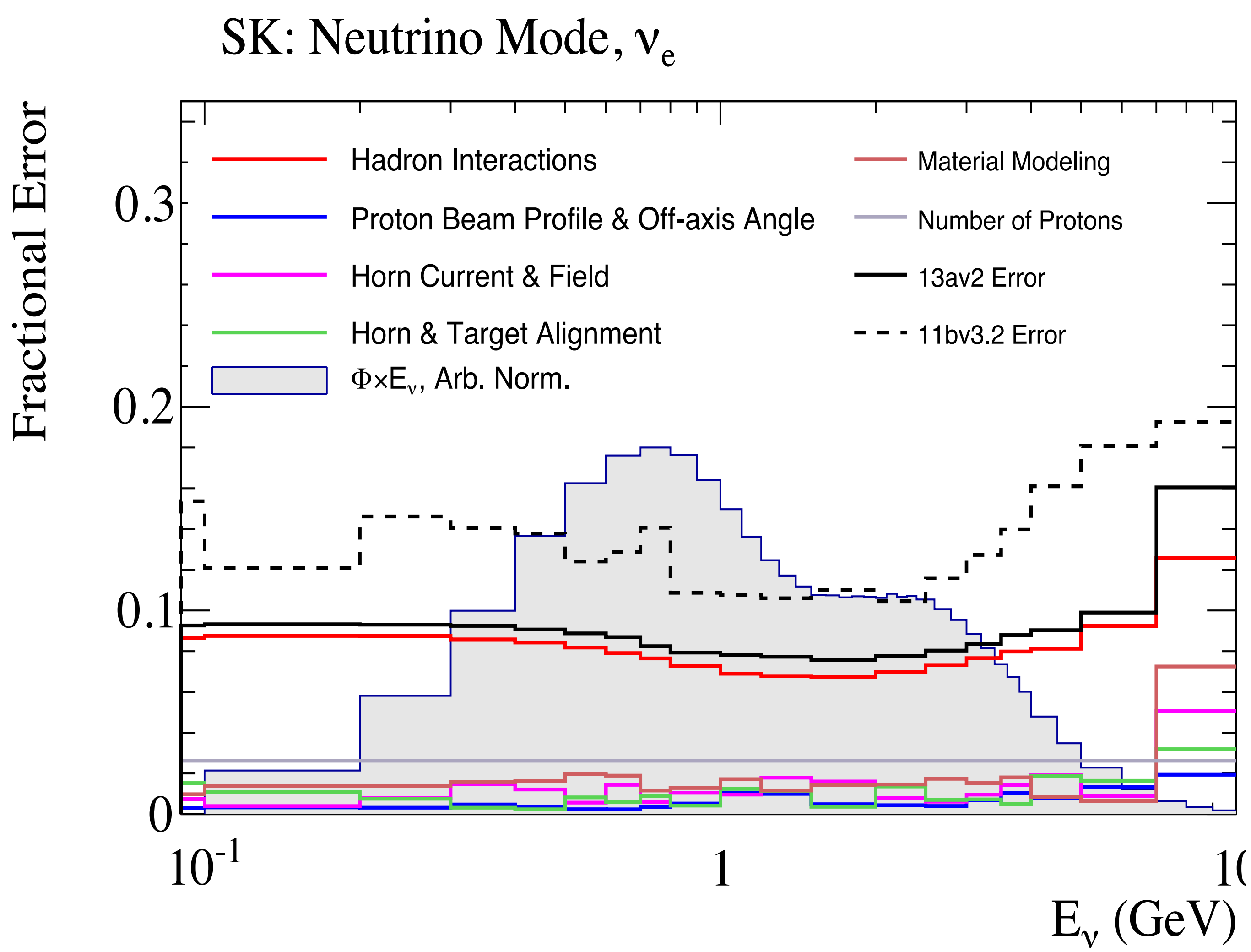


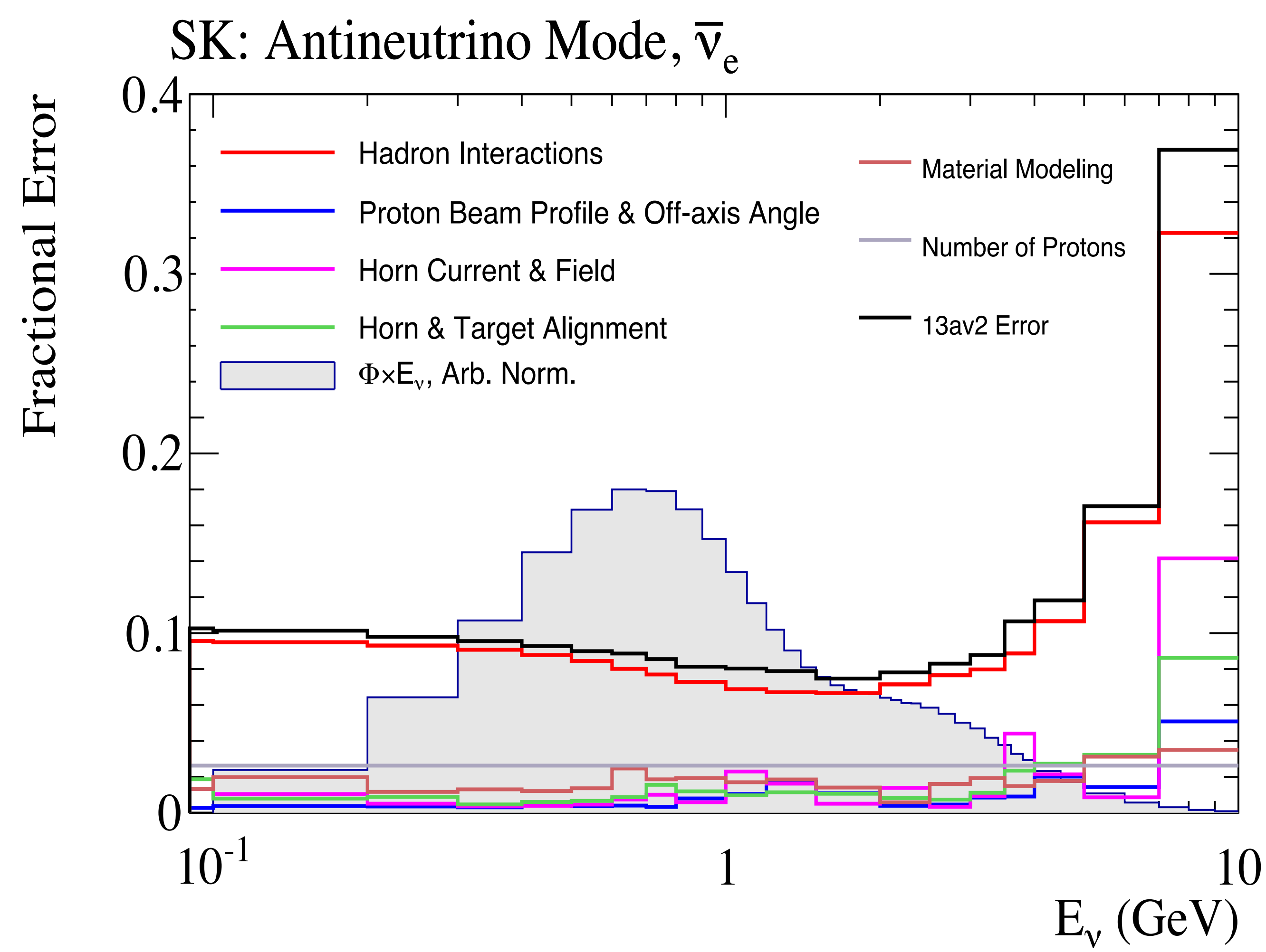
From: P69 WAGASCI proposal



- 2.5 deg off-axis spectra: electron, muon + antineutrinos
- Additionally, on-axis (grey) and (soon) 1.5deg off-axis (right)

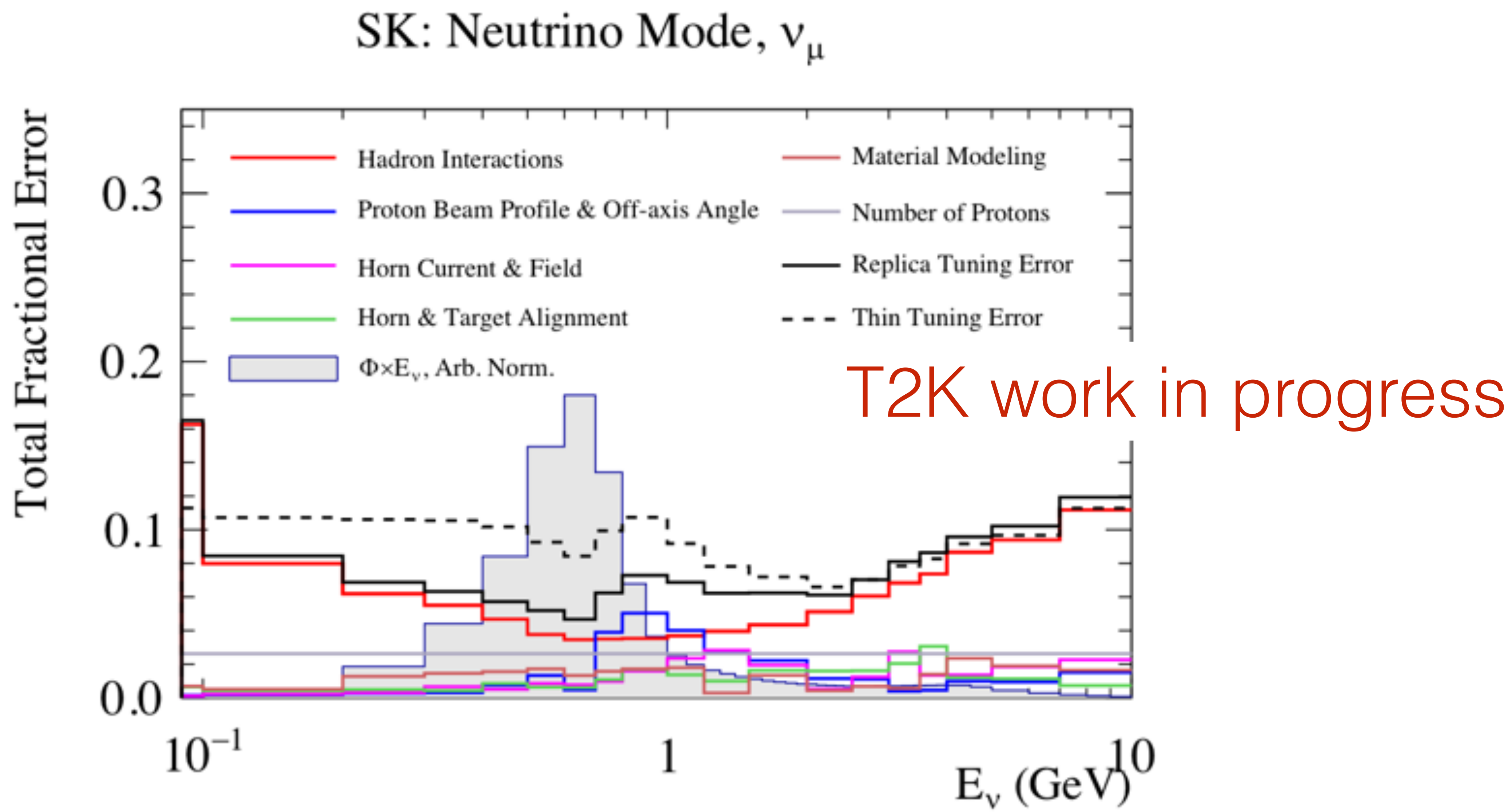
And the neutrino source uncertainty





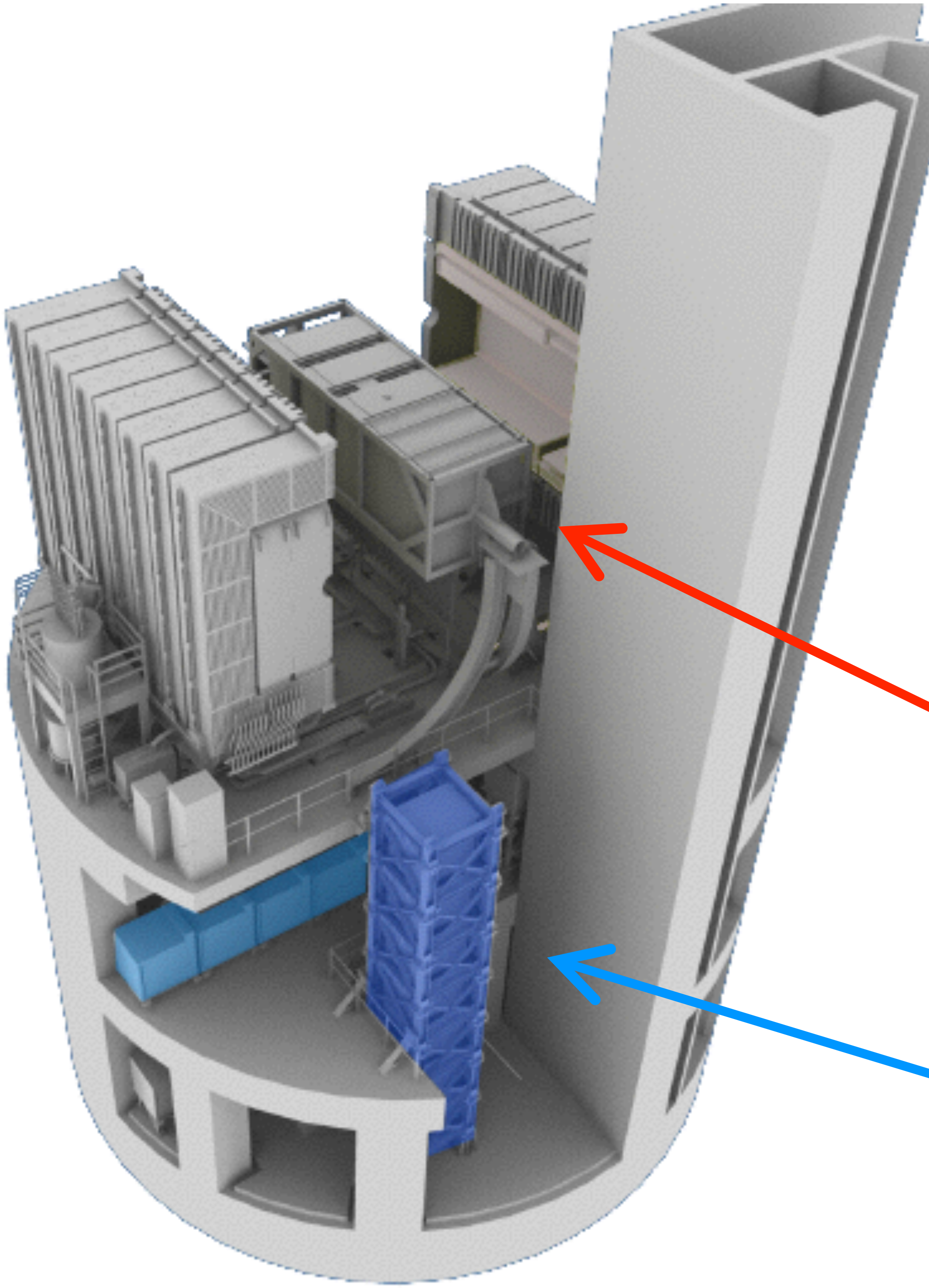
- Uncertainties at far detector (SK, ND) are currently ~10%
    - Include tuning from external measurements (e.g. NA61) and internal measurements (e.g. beam monitors)
- Combined measurements of on-axis + off-axis have (further reduced) relative uncertainties

And the neutrino source uncertainty

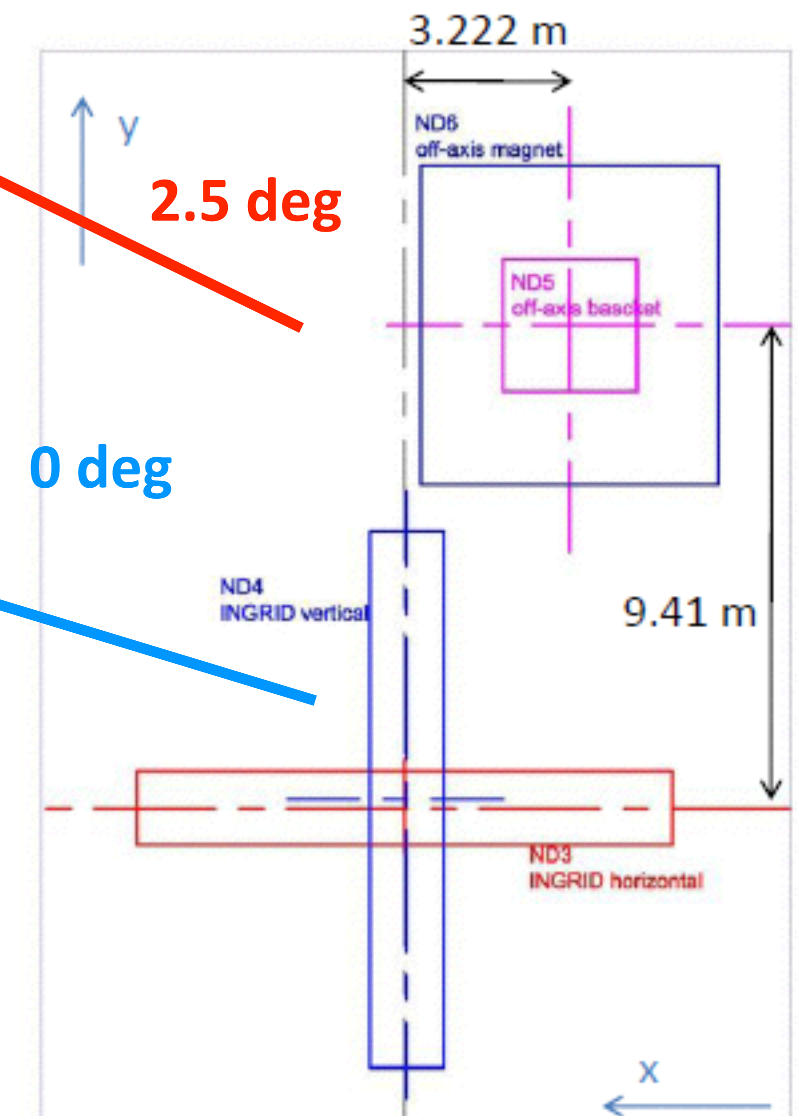


- Uncertainties at far detector (SK, ND) are currently ~10%
    - Steady improvement with time, expected update soon ~5% level)

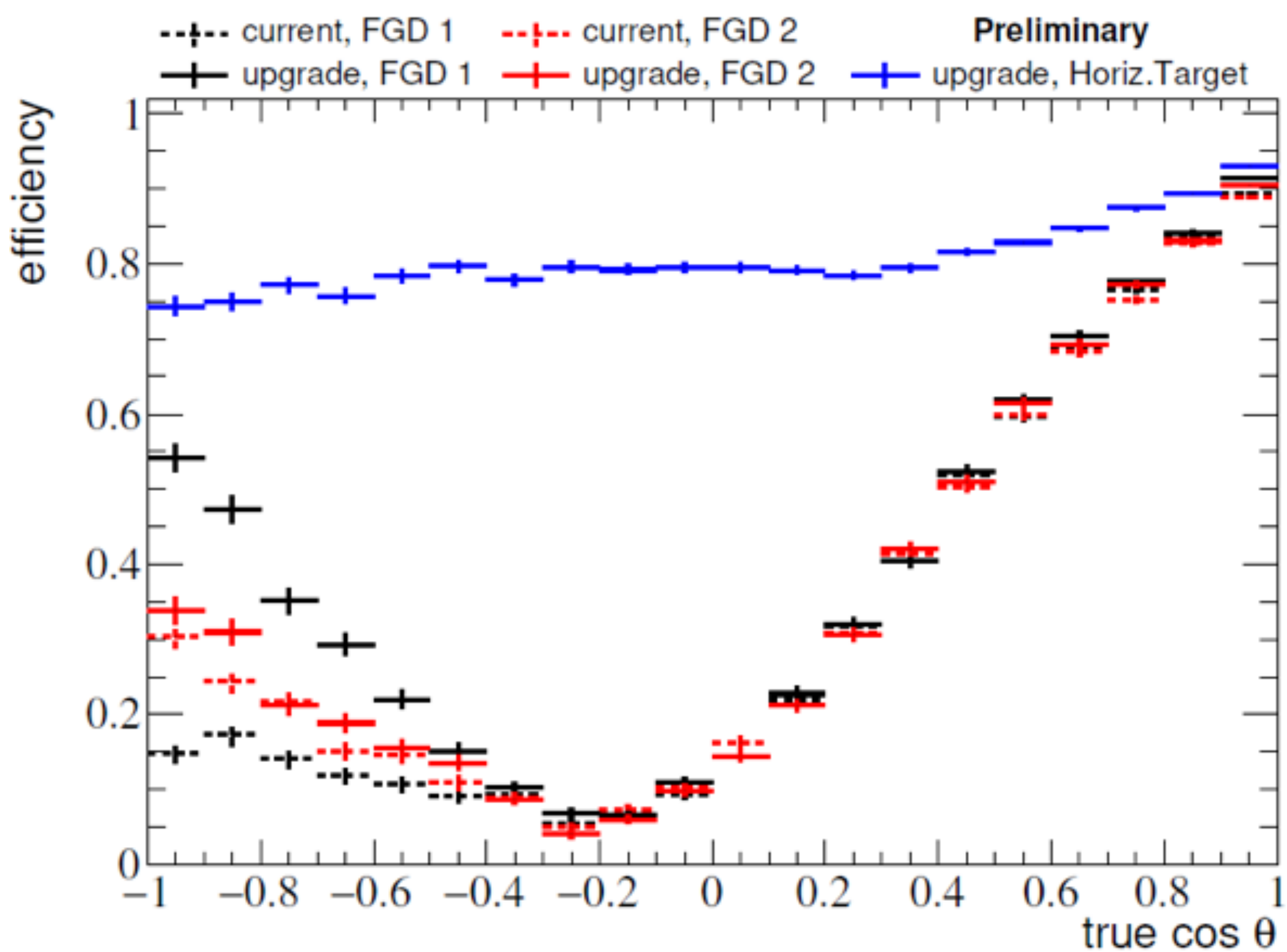
Detector capabilities



- Far detector SK: H2O
- **Off-axis ND280**->NDup: H2O, Ar, CH
- **On-axis INGRID**: H2O, CH, Fe



Detector capabilities: angular acceptance



- Far detector SK: 4π
- Off-axis ND280-> “ND upgrade”: improved acceptance
- On-axis INGRID: p_{μ}>500 MeV/c, $\cos(\theta_{\mu})$ > 0.26

Detector capabilities: proton acceptance

- Far detector SK: not possible
- Off-axis ND280: p_p>450 MeV/c, $\cos(\theta_p)$ > 0.4
- On-axis INGRID: p_p>500 MeV/c, $\cos(\theta_p)$ > 0.26

What are the current uncertainties are assigned to generators/theory for T2K analyses?

Oscillation analyses

Cross section analyses

(baseline) cross section nuisance parameters

(extended) cross section nuisance parameters

Impact of neutrino interaction uncertainties

Impact of neutrino interaction uncertainties

Cross section model parameters
format and role of uncertainties

- **A particular model may have inherent uncertainties**
  - e.g. Uncertainties from fits to external data
  - degrees of freedom within the model
- **An experiment may also add:**
- Uncertainty to represent alternate models (or closure tests— is alternate model reasonably represented by other uncertainties?)
- Uncertainty on assumptions (where the model is extrapolated)
- Uncertainty on implementation of the model

Cross section model parameters
an evolution…

T2K 2012

T2K 2018

Apologies - left NEUT versioning and specific models to Hayato-san's multiple talks…

T2K 2017

Cross section model parameters
an evolution…

T2K 2012

- Single QE model
- no 2p2h

T2K 2018

- Baseline QE model: LFG+RPA (Nieves et al)
- Alternate models: SF (Benhar et al), Z-expansion form factors
- Consistent 2p2h model with baseline QE model

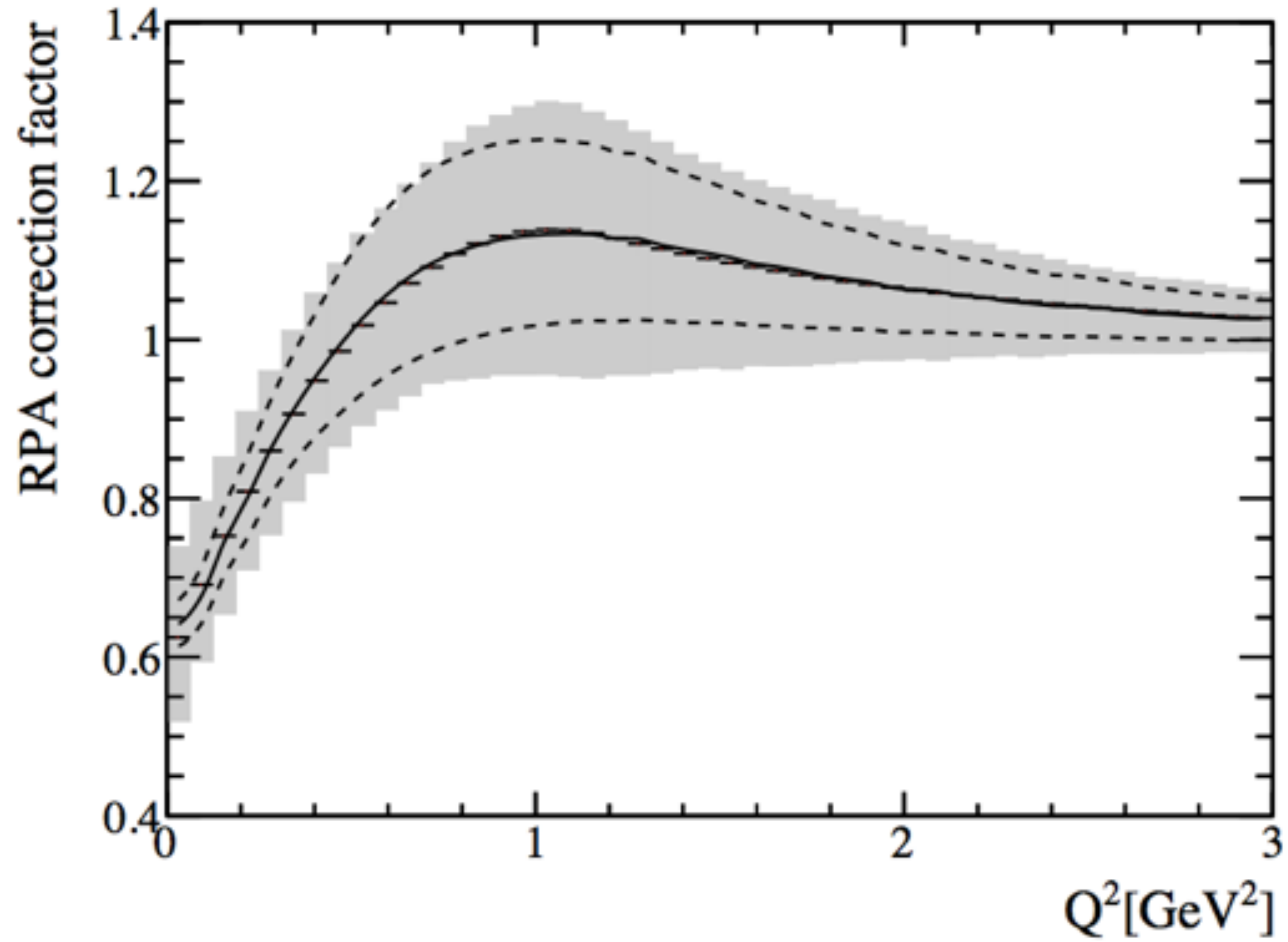
T2K 2017

- Baseline QE model: RFG+RPA (Nieves et al)
- Alternate models: SF (Benhar et al), Z-expansion form factors

Uncertainties on QE part of the model

- Effective RPA uncertainties assigned based on Nieves et al: *Phys.Lett.B638:325-332 (2006)*:

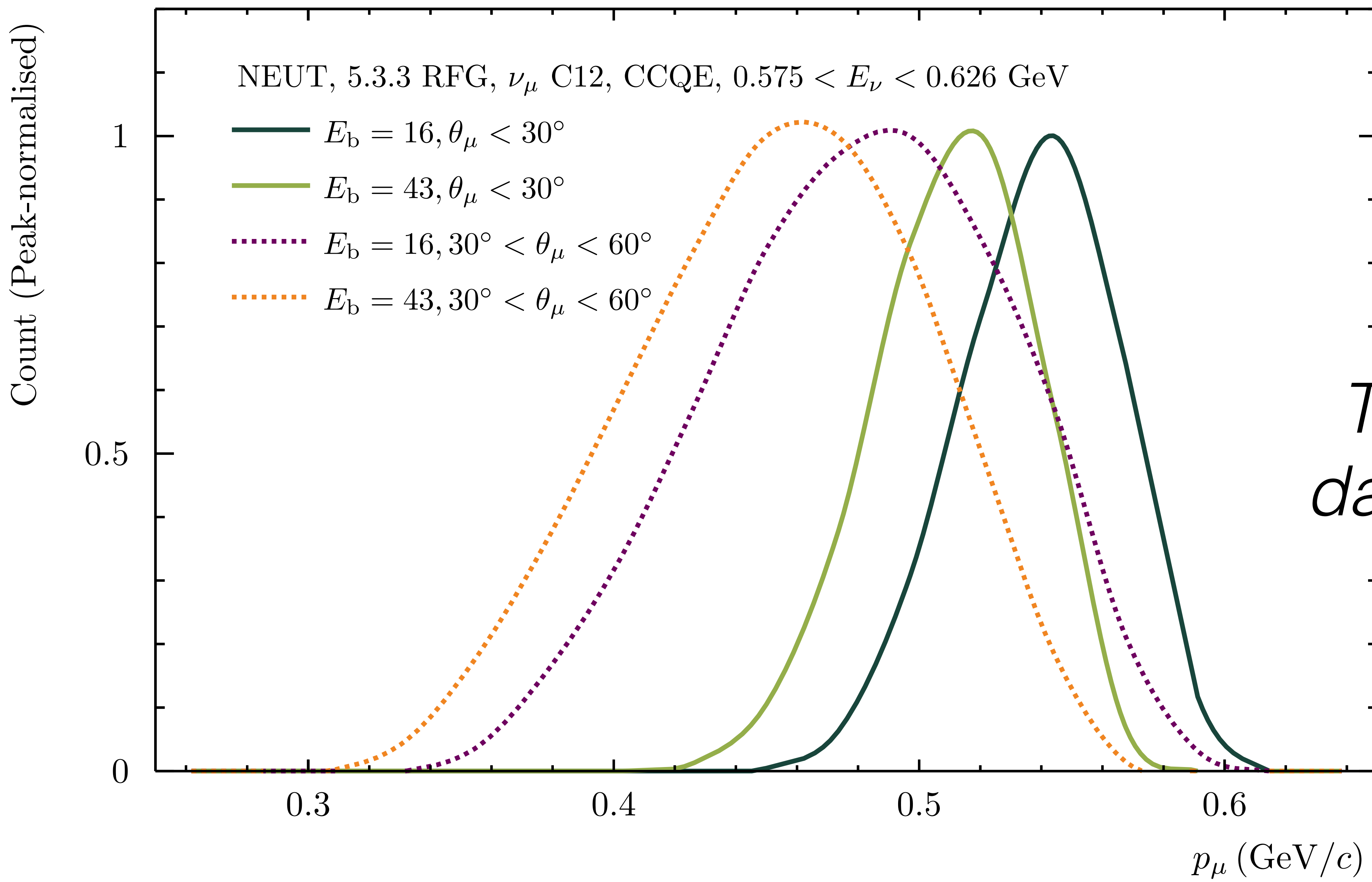
- 5 parameters, 4 varied, 1 fixed; *parameterization chosen by experimentalists*



- MAQE nu-C (effective): 1 parameter (nu-H (MAQE) is 1.03 and fixed)

- pF (C) and pF (O): 2 parameters

What is this “E_b”?



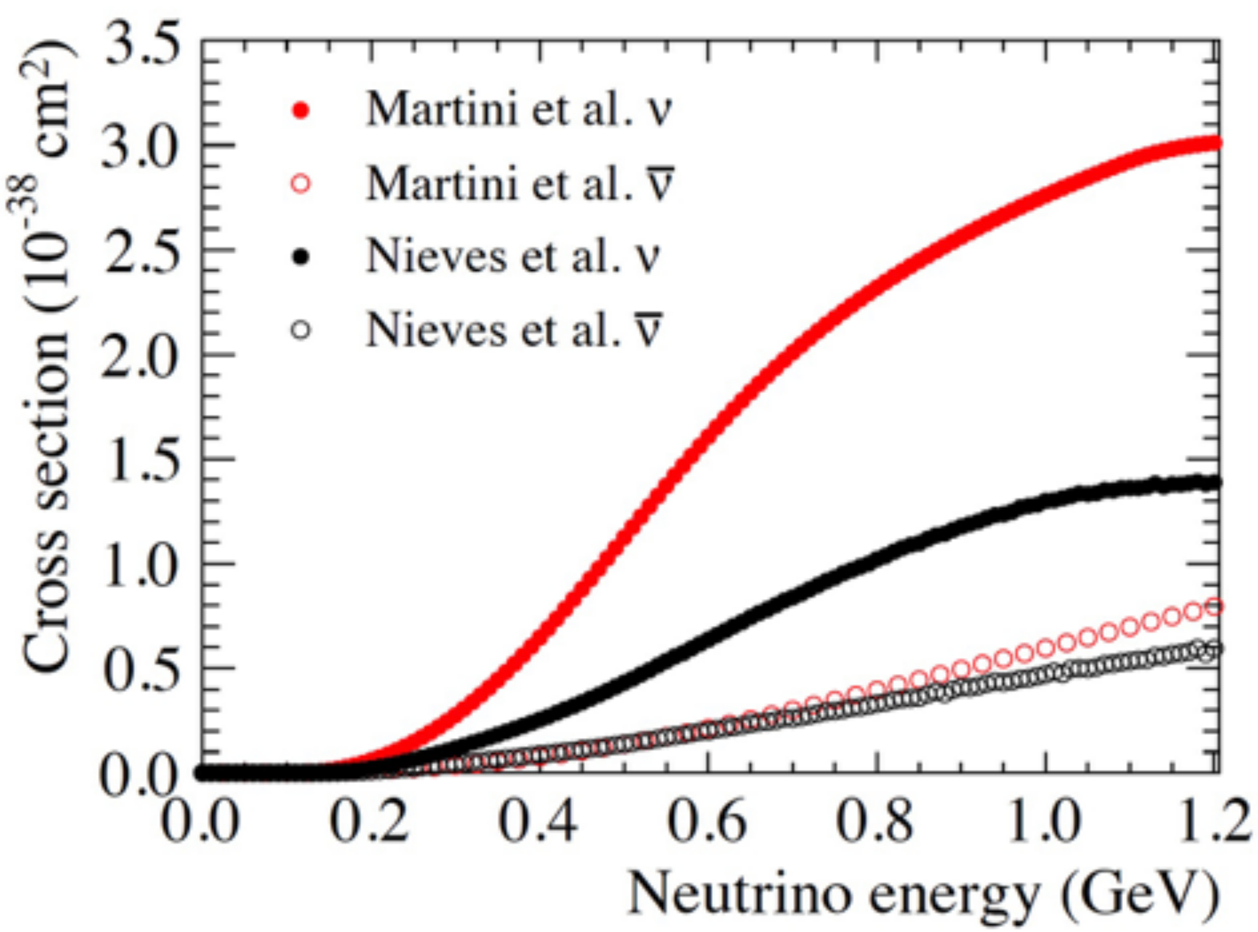
Discussion in Bodek, arxiv1801.07975

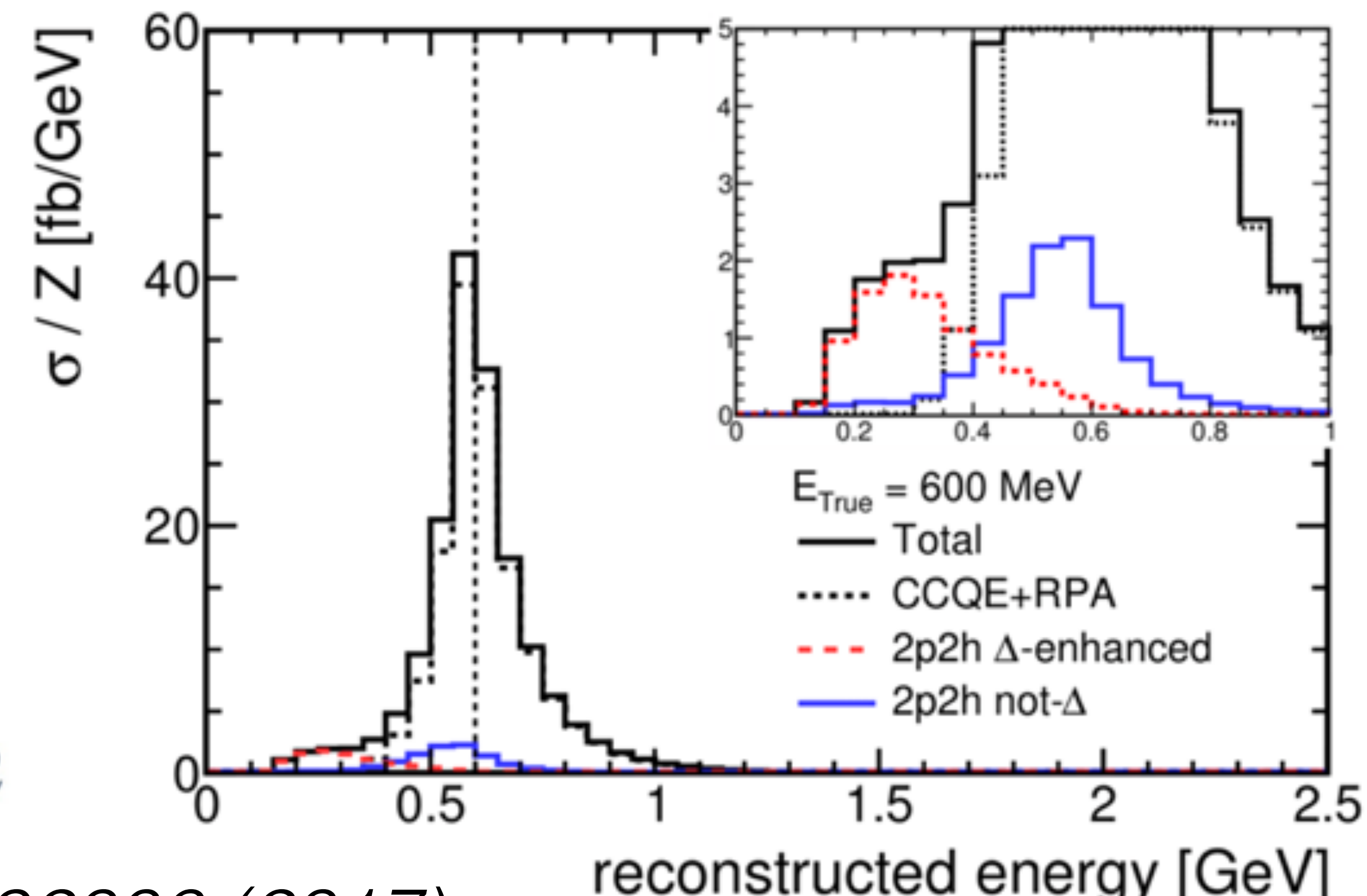
Tested in “fake data” - will revisit

- Separation energy or removal energy; not really a single number, associated to a particular model
- Shifts relationship between observables (p_μ) and E_ν

Uncertainties on 2p2h part of the model

- Include overall strength (normalization on neutrino, and antineutrino component) - 2 parameters
- Attribute strength to most energy-biasing (Delta-like terms) and not and and non-Delta like - 2 parameters
- Carbon to oxygen scaling factor - fully correlated between nu/nubar: 2 parameters





PRD 96, 092006 (2017)

Uncertainties on resonance part of the model

- 3 parameters set from fits to bubble chamber data, with correlations

Parameter	Central Value	Uncertainty
M_A^{RES}(GeV)	1.07	0.15
C_A^5	0.96	0.15
$I_{1/2}$	0.96	0.40

- Additional "fake data" tests of "Minoo" model - *will revisit*

T2K cross section analyses

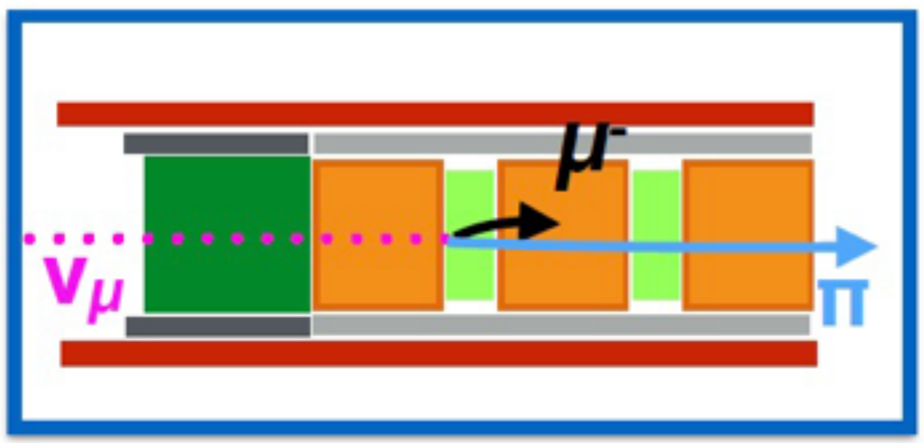
- **Generally, additional uncertainties for cross section analyses**
- Oscillation analysis is focused on sufficient uncertainties for SK samples; cross section selections can cover wider range of target materials, processes and kinematics
  - Selection dependent, so can be unique to a particular analysis - *apologies no summary here*
- Similar “method” as oscillation analysis, goal to avoid dependance on model uncertainties or inflate if necessary to avoid bias.
  - Baseline uncertainties from oscillation analysis
  - Include additional uncertainties, iterate
    - May reduced phase space or modify selection
  - Closure tests of alternate models to demonstrate completeness. Do you extract a given model with the correct uncertainties?

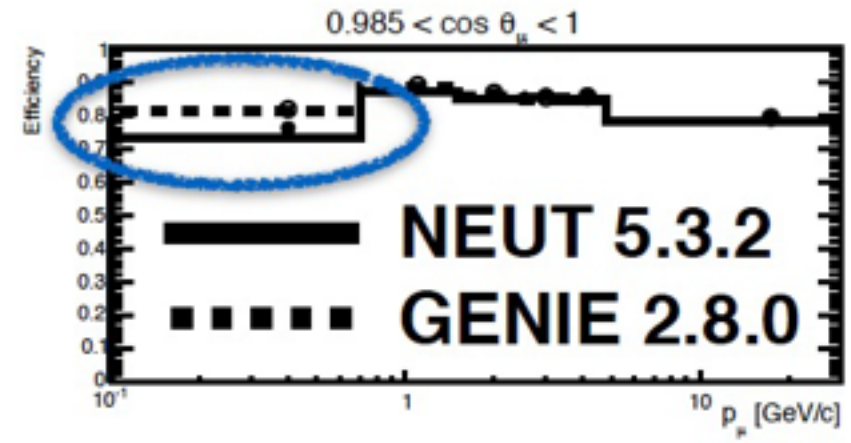
T2K cross section analyses

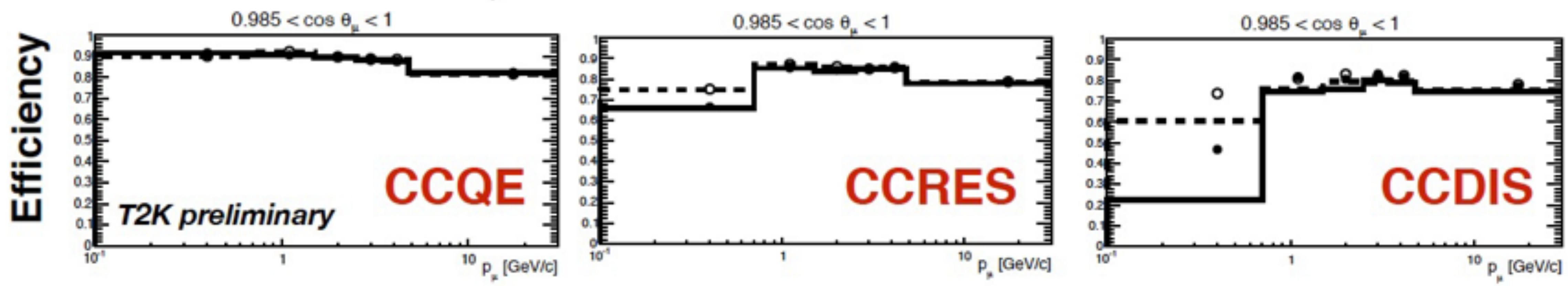
$$\frac{d\sigma}{dp_{\mu,i}dcos\theta_{\mu,j}} = \frac{N_{ij}^{CC-\mu}}{\epsilon_{ij}^{CC-\mu,MC}\Phi N_{nucleons}^{FV}\Delta p_{\mu,i}\Delta cos\theta_{\mu,j}}$$

A. Garcia, NuInt2017

- Efficiency correction using NEUT 5.3.0 and GENIE 2.8.0 predictions.
  - Discrepancies for low momentum muons going forward (in RES and DIS channels).







- Impact of models is important for cross section analyses
- Alternate models can be fully simulated (GENIE, NuWro and NEUT) or tested with template weights (e.g. Minoo model…)

T2K overall uncertainty budget

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 overall uncertainty budget

Error source	1-ring μ-like		1-ring e-like			
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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 $\nu_\mu \rightarrow \nu_e$ inferences

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

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

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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)

  Also includes "photonuclear" effect

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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

T2K overall uncertainty budget

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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 overall uncertainty budget

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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**
  - Theoretically driven uncertainty, difficult to probe experimentally, 1 parameter

T2K overall uncertainty budget

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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, 1 parameter

“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:

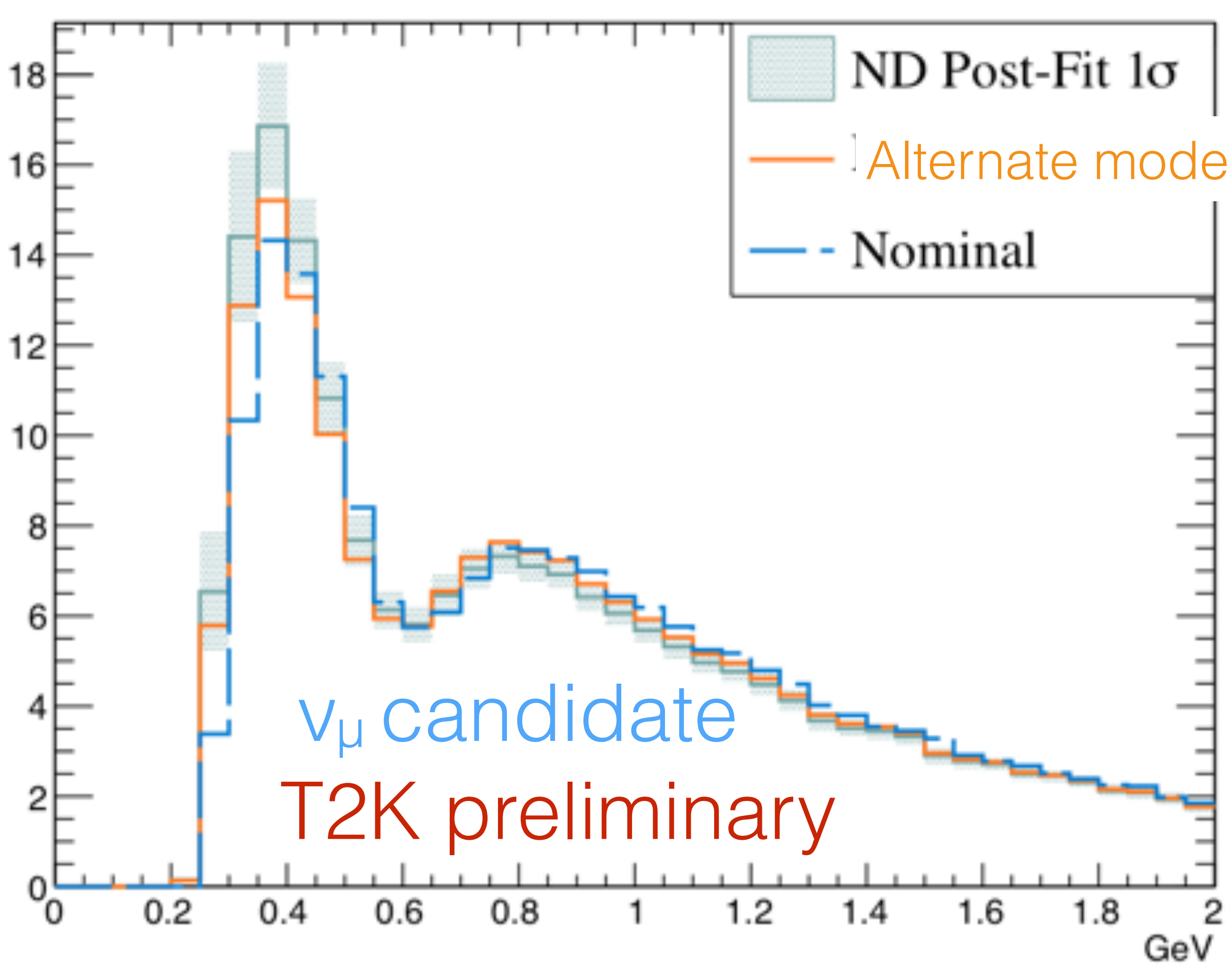
    - Prepare an alternate model, and include it in the analysis as if it were data

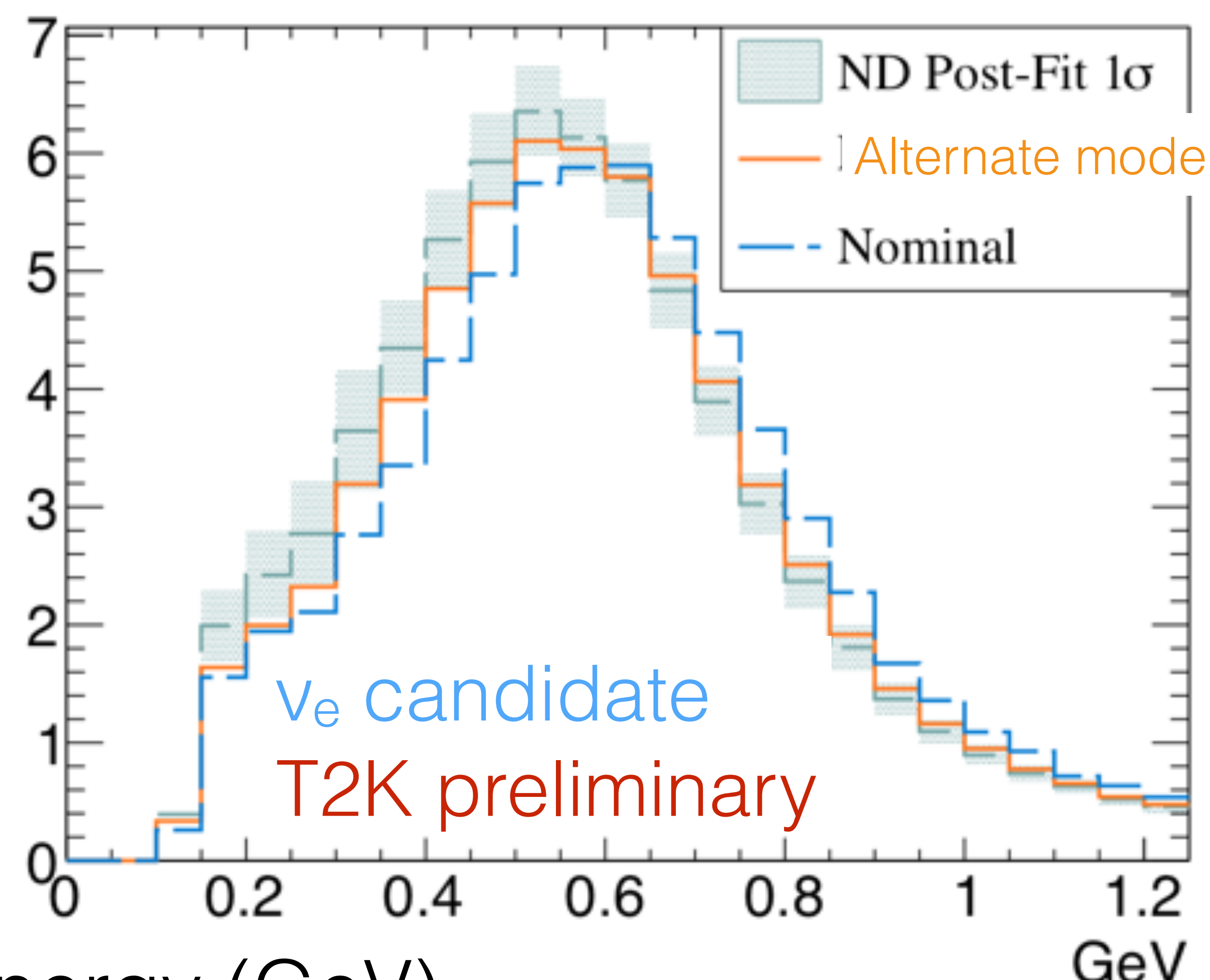
    - Run entire T2K oscillation analysis chain (fit near detector with nominal cross section uncertainties and propagate) to evaluate effect on oscillation parameters

    - 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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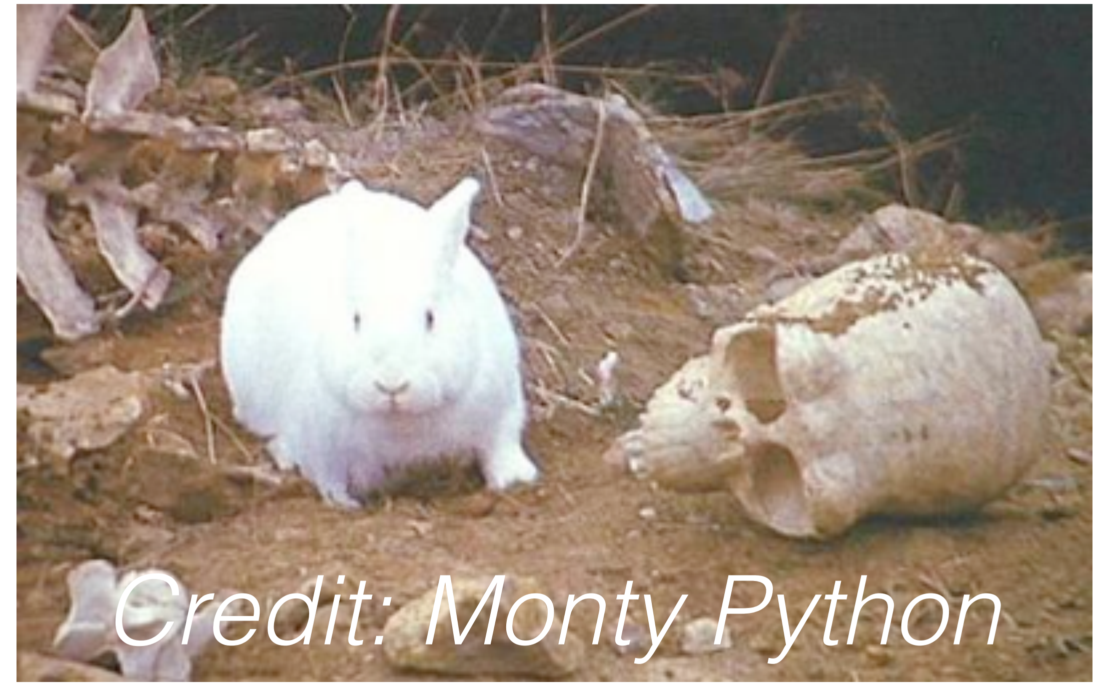
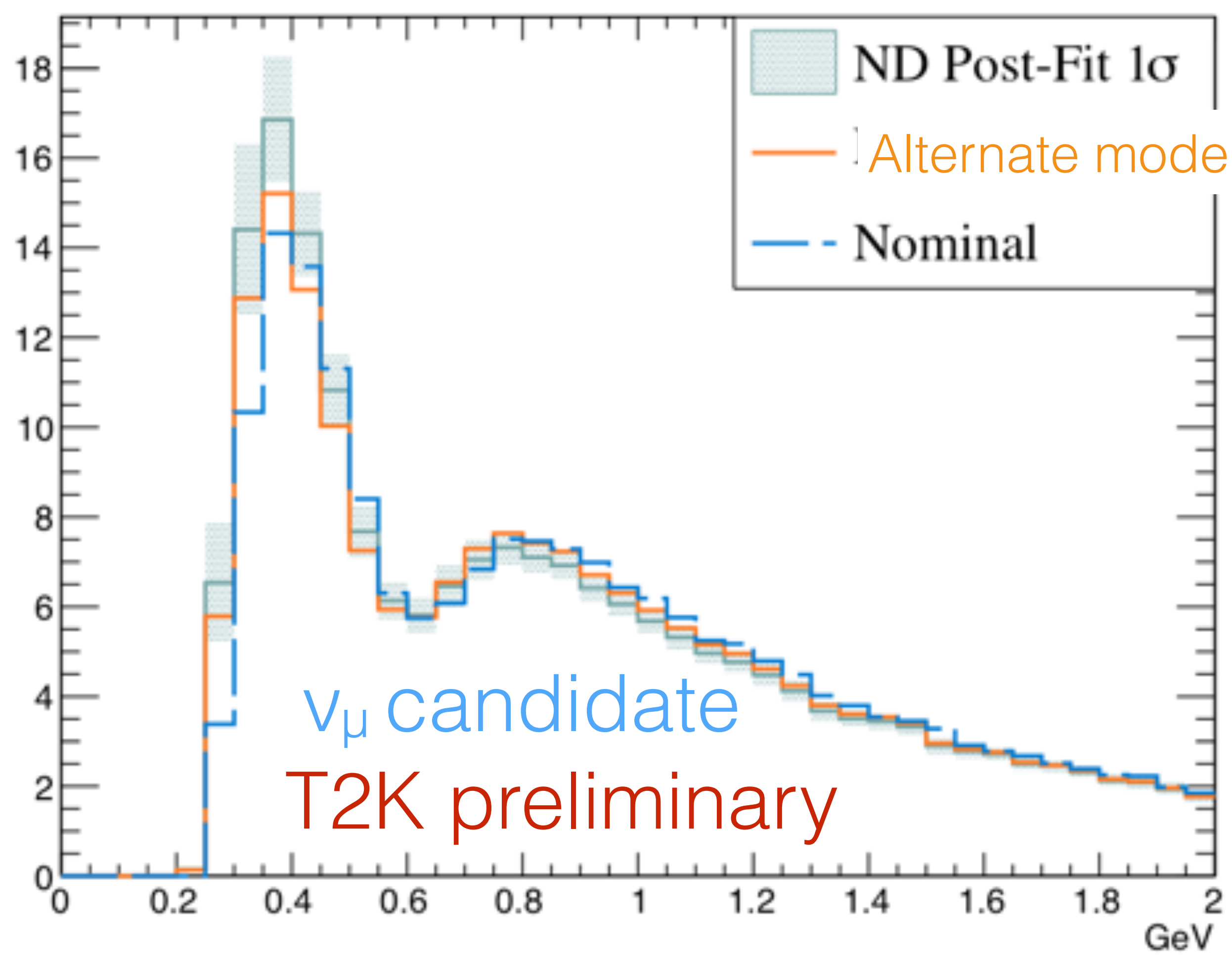
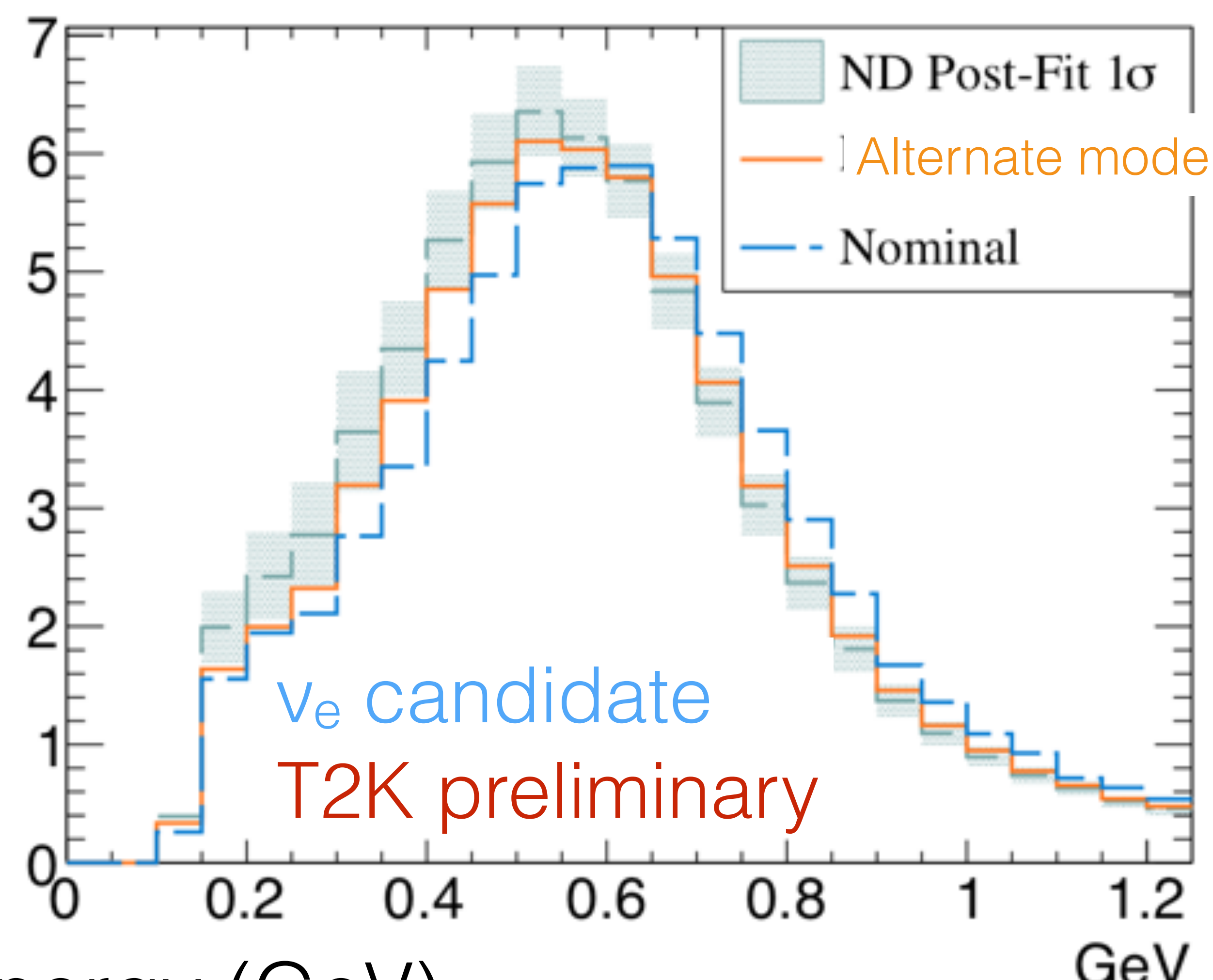


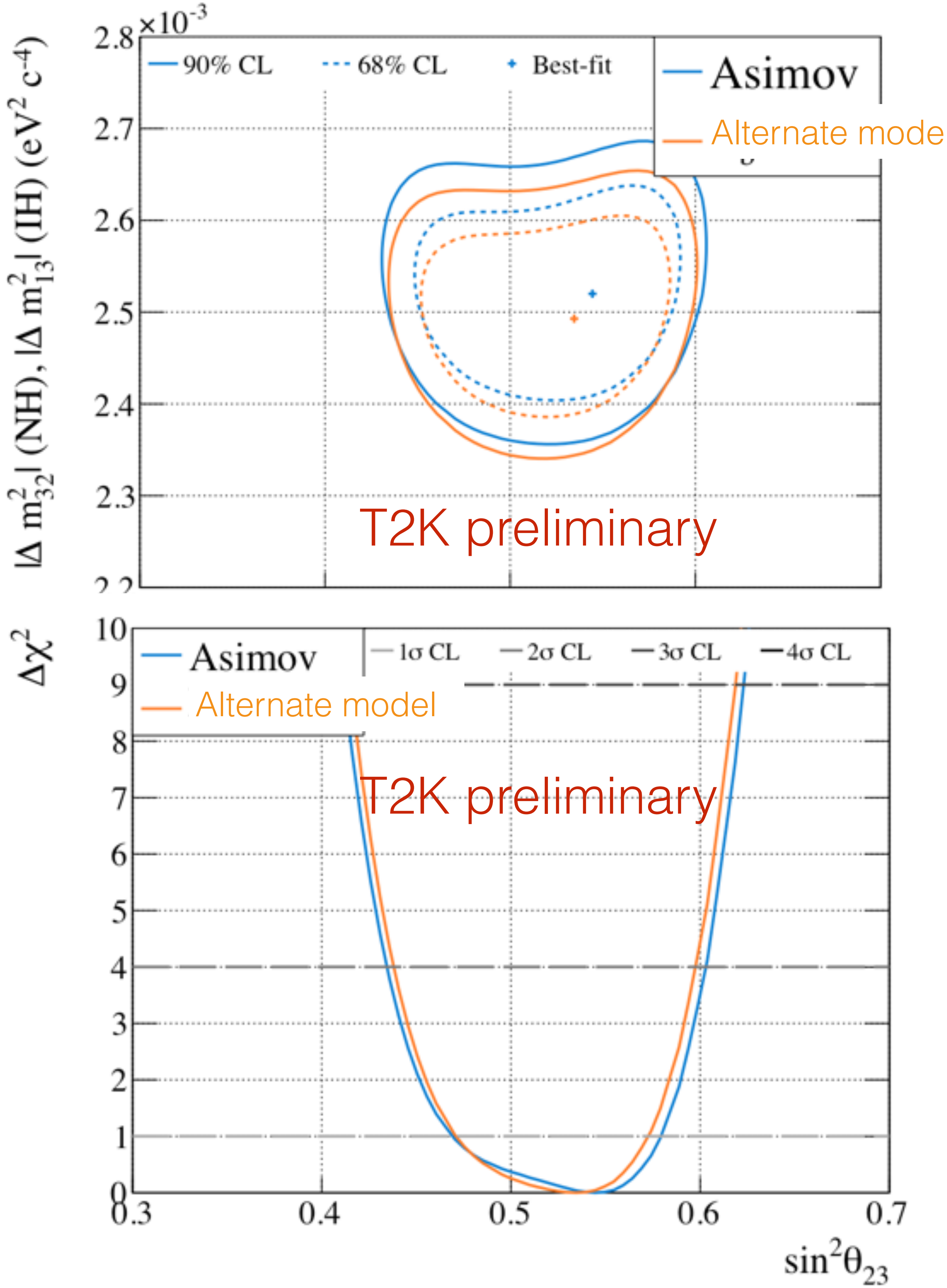




Reconstructed energy (GeV)

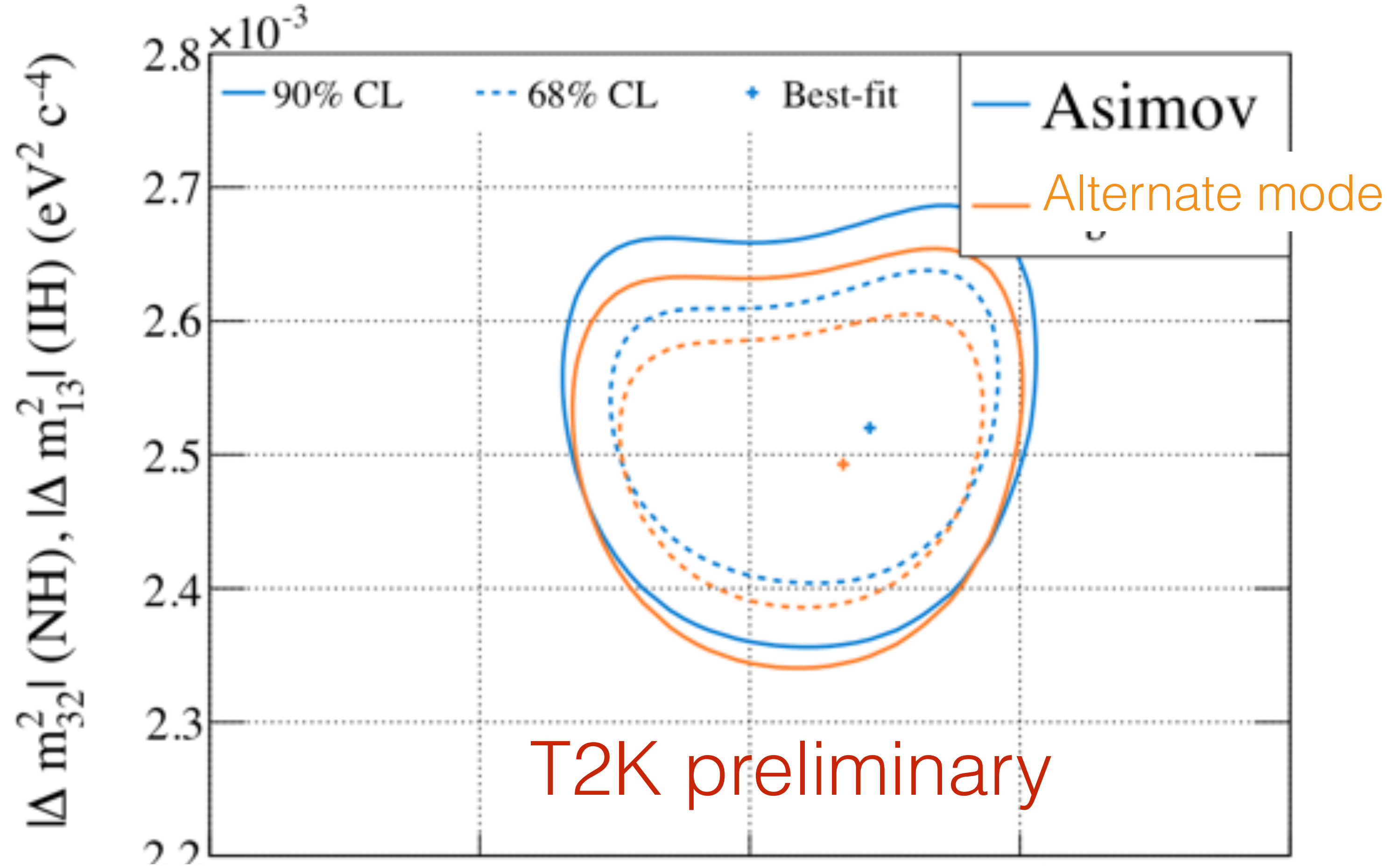
- Alternate models may create biases for current analysis; T2K adds additional uncertainty

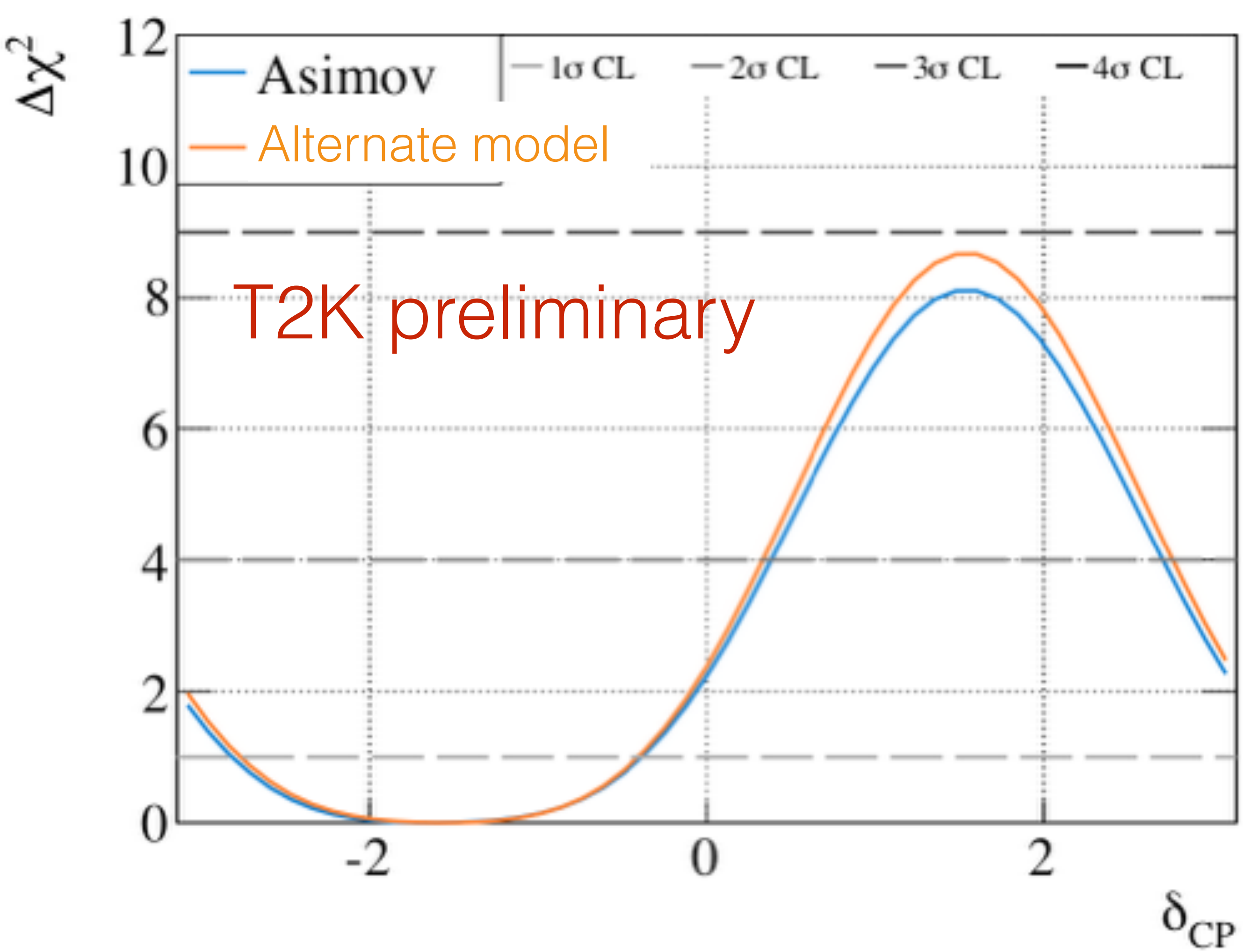
- We mustn't run away!

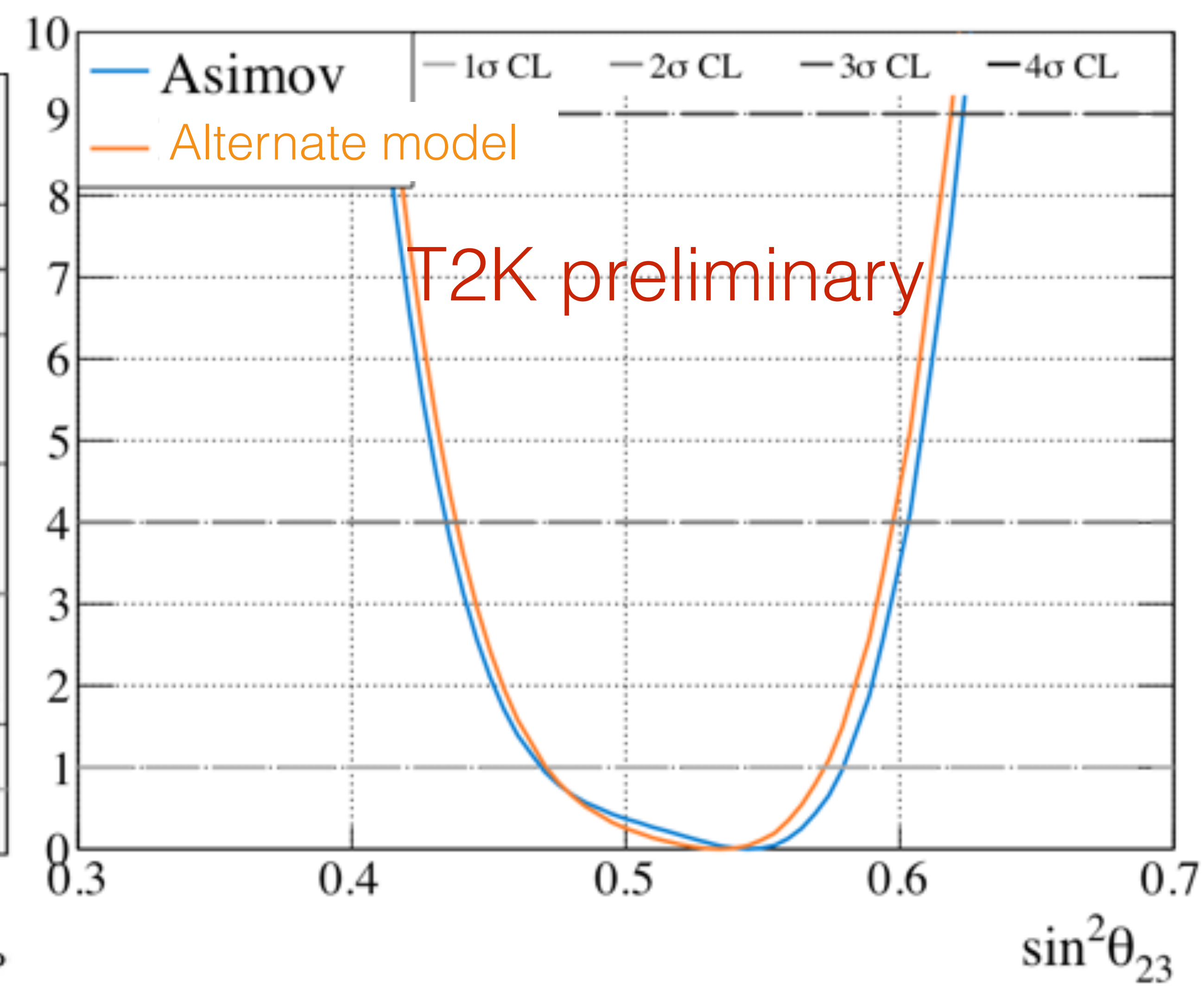


- Alternate models may create biases for current analysis; T2K adds additional uncertainty

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

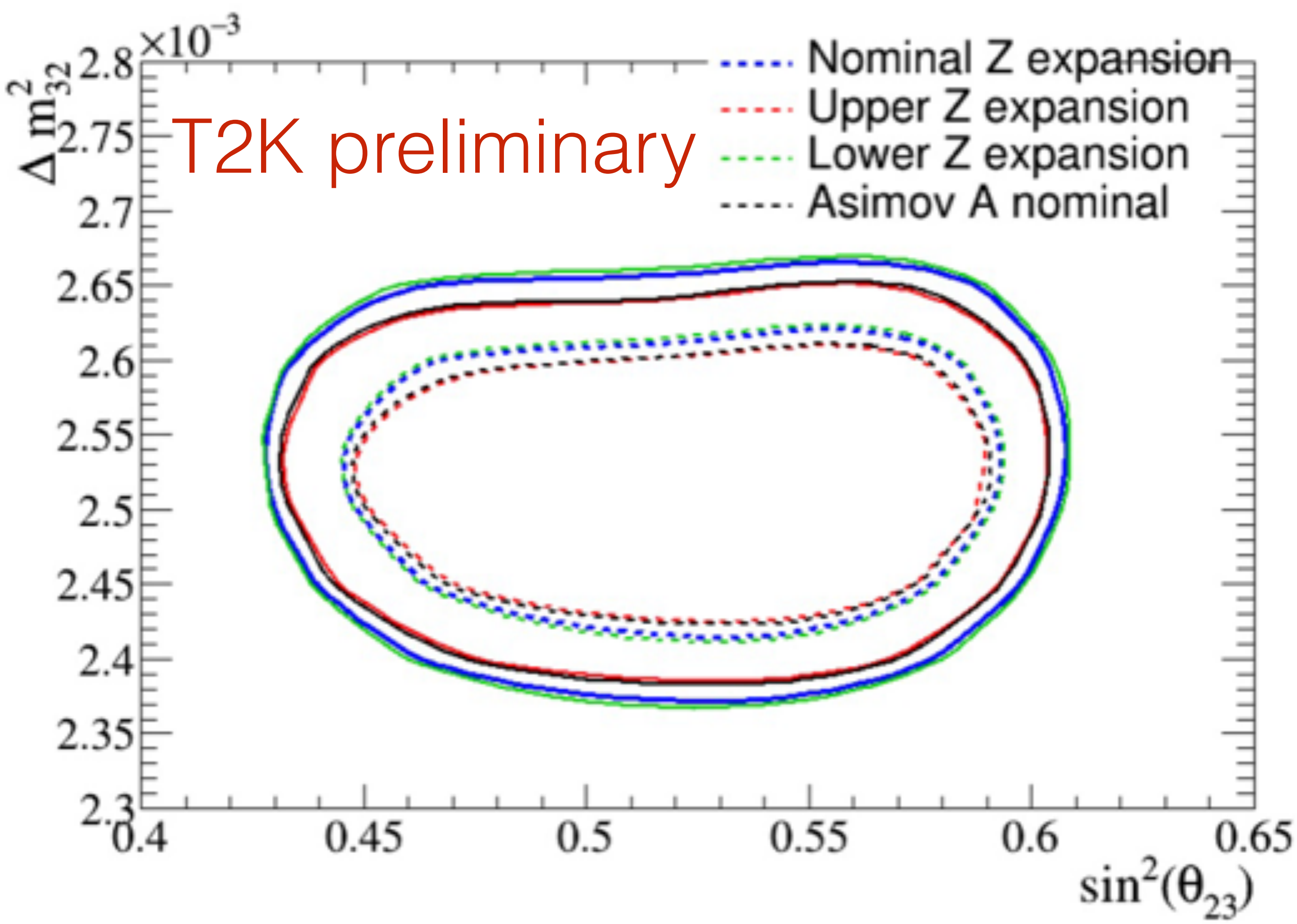


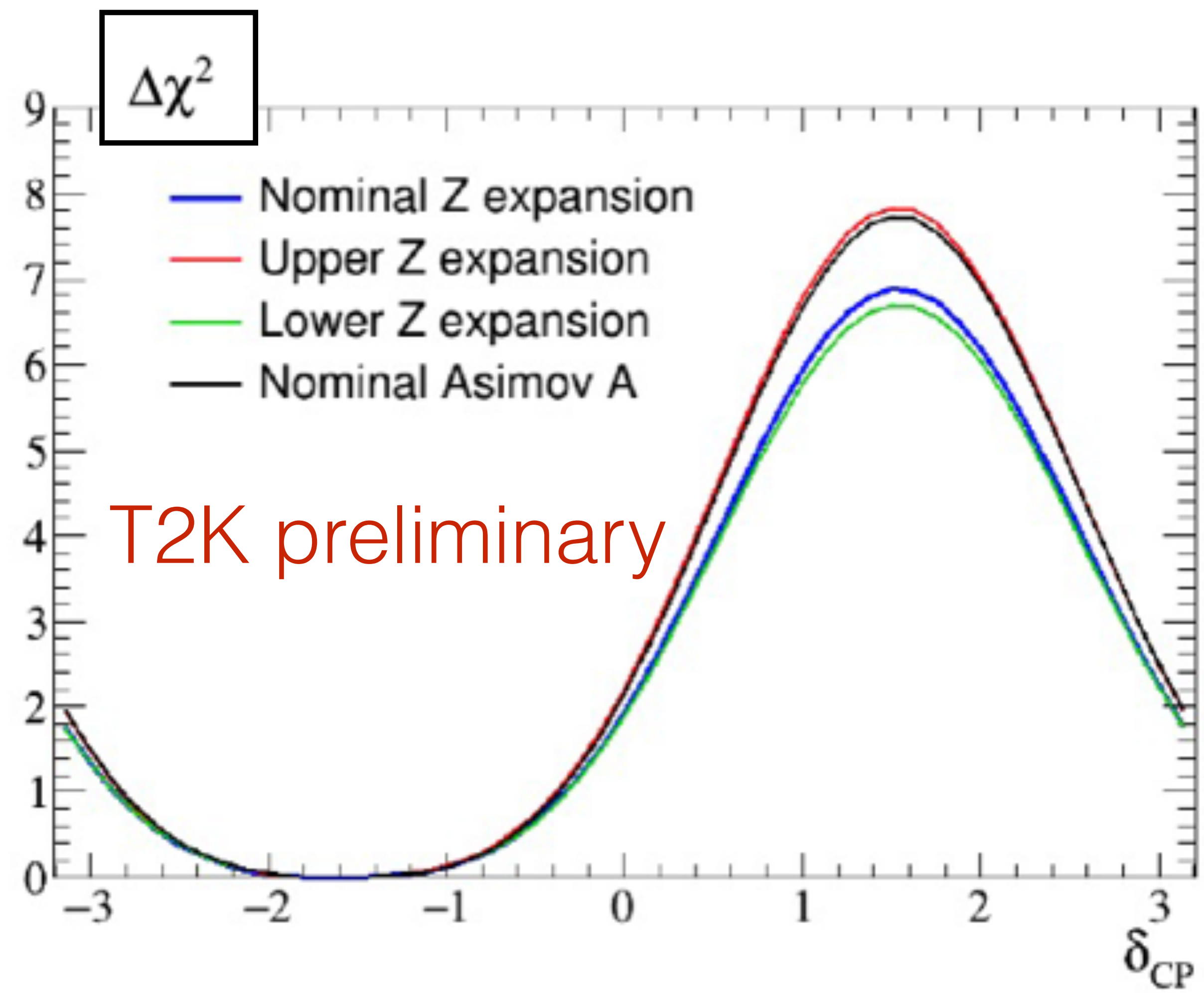




Studies on impact of alternate form factor

- 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…

List of alternate model tests

QE+2p2h

- Benhar et al QE (SF)
- Martini et al 2p2h
- Alternate form factors (2 studies)
- Binding energy

Resonance

- Minoo model + NEUT bug fix
- Multipion production multiplicity improvement
- Alternate form factors

Data-driven

- Differences in pion kinematics at ND280
- Attribute data/model differences muon kinematics to 1p1h or 2p2h and propagate (ND280, MINERvA inspired: 2 studies)

Many of the alternate model tests showed an impact on the atmospheric parameters and uncertainties were increased

Challenge for current statistical uncertainty

What is experimental interface to input communities?

- **What projections of uncertainties 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 details of the parameterization are valuable to provide?**
  - Best parameters are ones which are representative of the physics, and which we can agree for the same projection in theory/experiment

Experimental community feedback

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 v and v 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 (MINERvA, NOvA, SK nue 1pi sample)
  - Is there 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*

Summary: what we know from oscillation analyses

- **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 where we can each provide information for comparison:**
  - 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

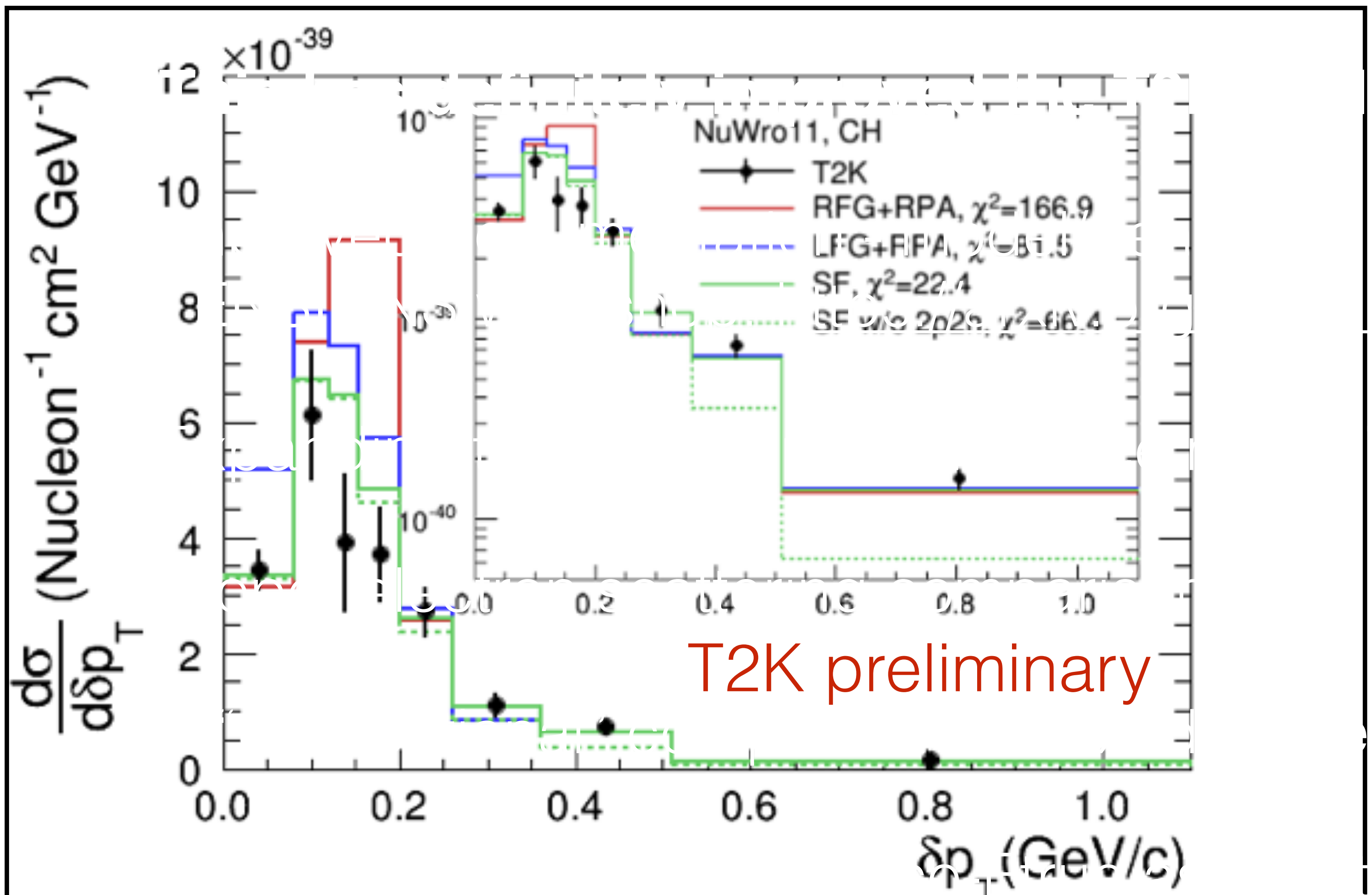
What are open questions/current lines of study?

T2K's future

hadronic state: protons, neutrons and pions

- New proton information from CC0π comparisons

- T2K will soon use neutron information (SK gadolinium doping) - *see Hayato-san's talk*



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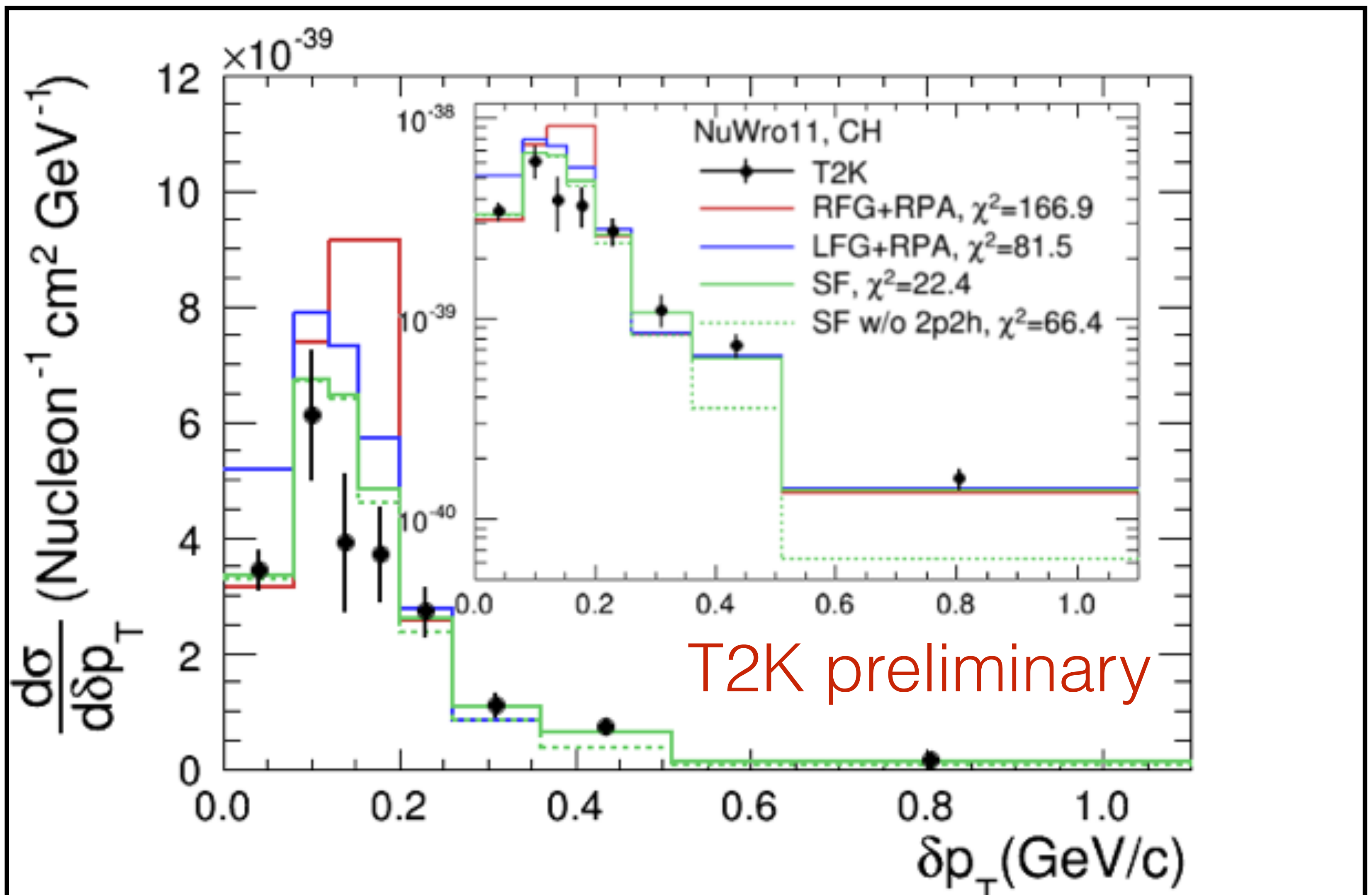


- Inclusive + protons != semi-inclusive

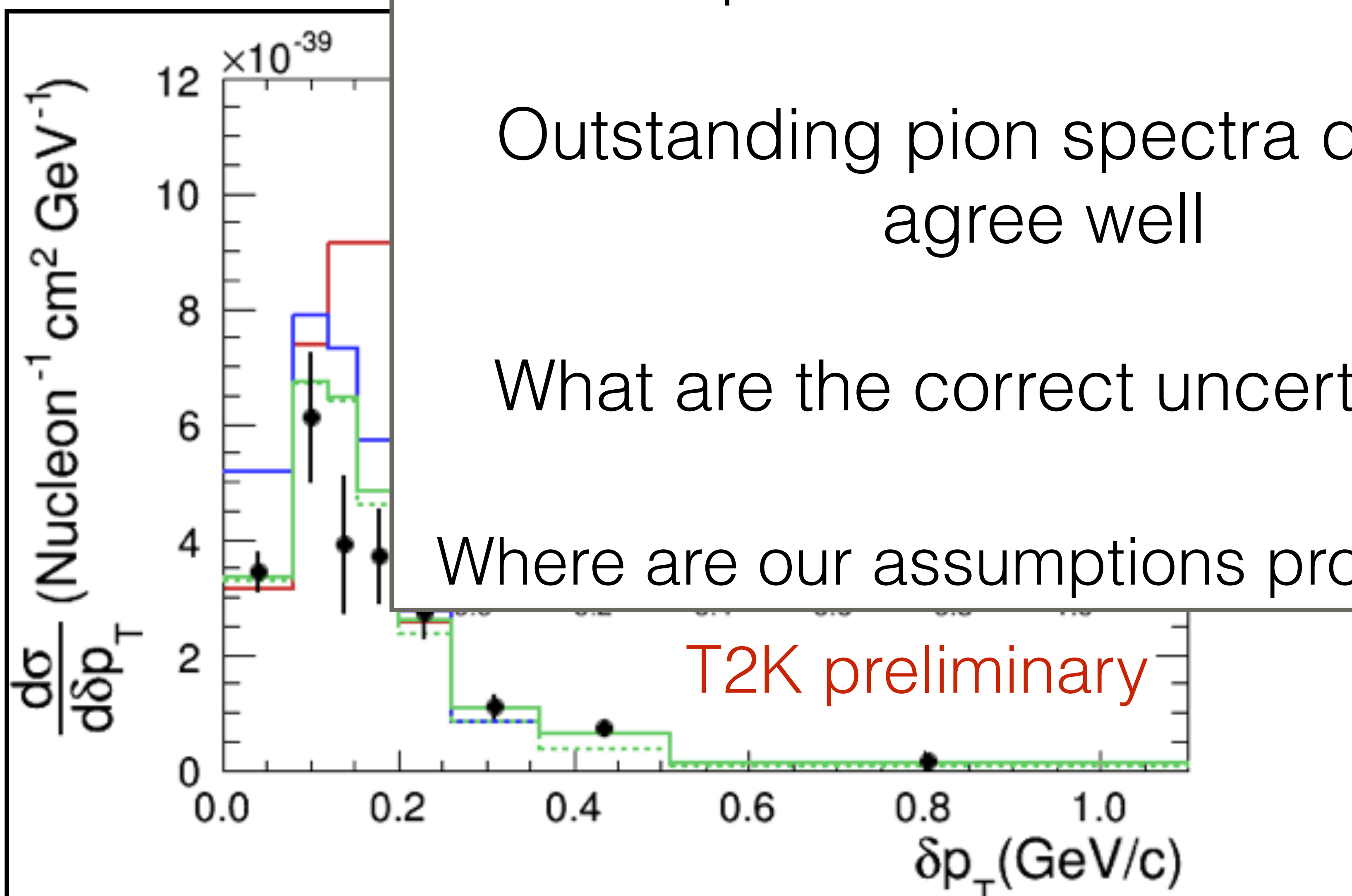
- What are the correct uncertainties?

- Where are our assumptions problematic?

T2K's future

hadronic state: protons, neutrons and pions

- New proton
- T2K will soo g) - *see Hayato-san's talk*



ve + protons !=
clusive

re the correct
inties?

- Where are our assumptions problematic?

Also, pions… - *see Hayato-san's talk*

T2K to include CC1π+ with visible pion sample in oscillation analysis

Outstanding pion spectra does not agree well

What are the correct uncertainties?

Where are our assumptions problematic?

What am I worried about?

consistency, validation, and transparency

- The usual T2K cycle is: compare to new models, data sets // update error // refine assumptions

What am I worried about?

consistency, validation, and transparency

- The usual T2K cycle is: compare to new models, data sets // update error // refine assumptions
- **What do we need to go forward from here?**
  - Improved documentation - model/generator dedicated papers? TENSIONS workshop: https://arxiv.org/abs/1805.07378
  - Expanding theory comparisons - see next slides
    - Especially, inclusive + hadrons != semi-inclusive
  - Proper electron scattering comparisons
    - “conventional” comparisons at fixed angle - we must face this
    - Direct comparison of Ereco-Etrue association for at least vector part in generators - see Adi’s talk

Example theory+experiment idea

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

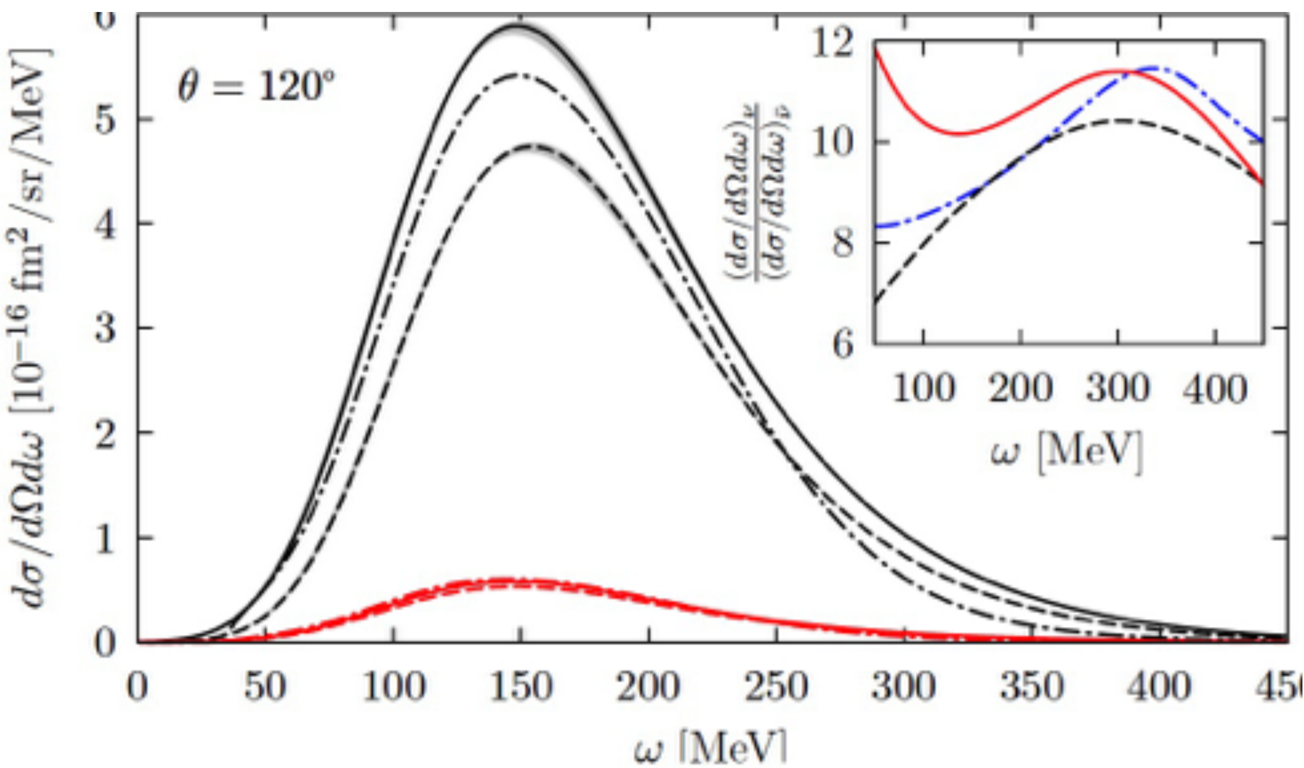
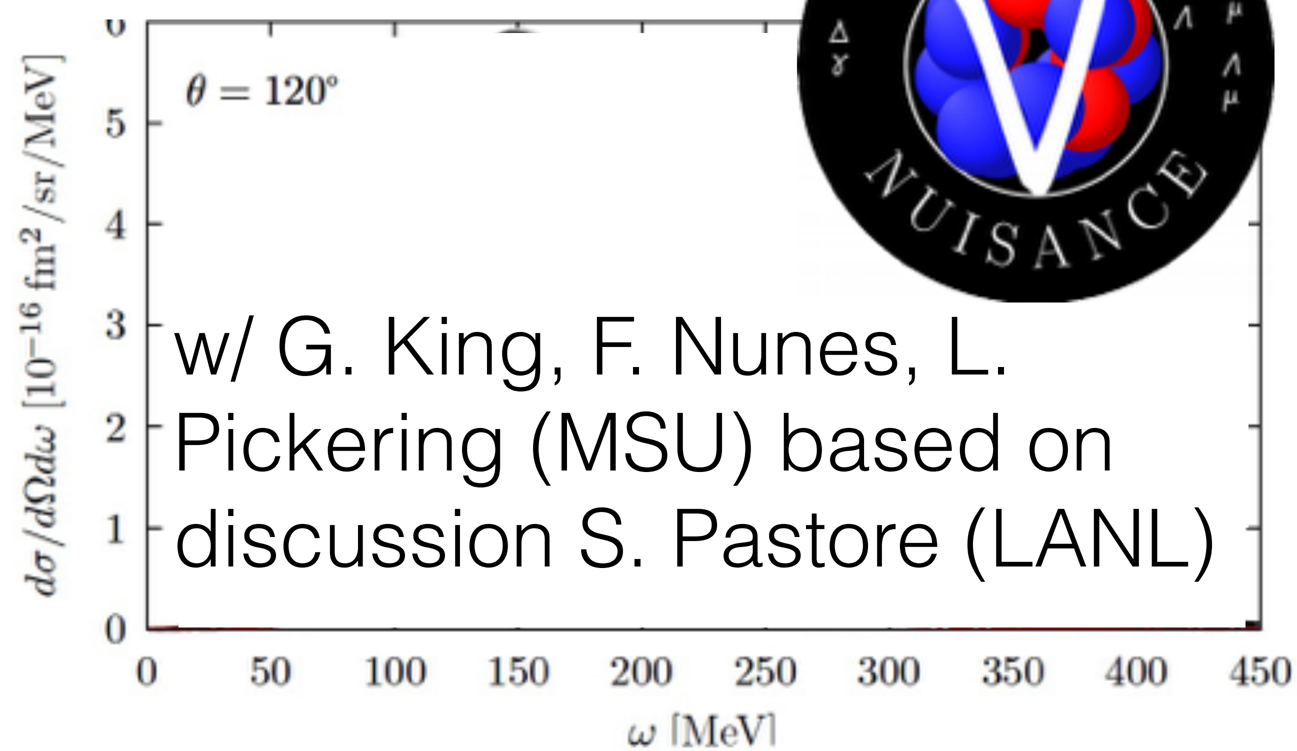


FIG. 2. (Color online) Weak neutral ν (black curves) and $\overline{\nu}$ (red curves) differential cross sections in ^{12}C at $q=570$ MeV/c, obtained with one-body only and one- and two-body terms in the *NC*. The final neutrino angle is indicated in each panel. The insets show ratios of the ν to $\overline{\nu}$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

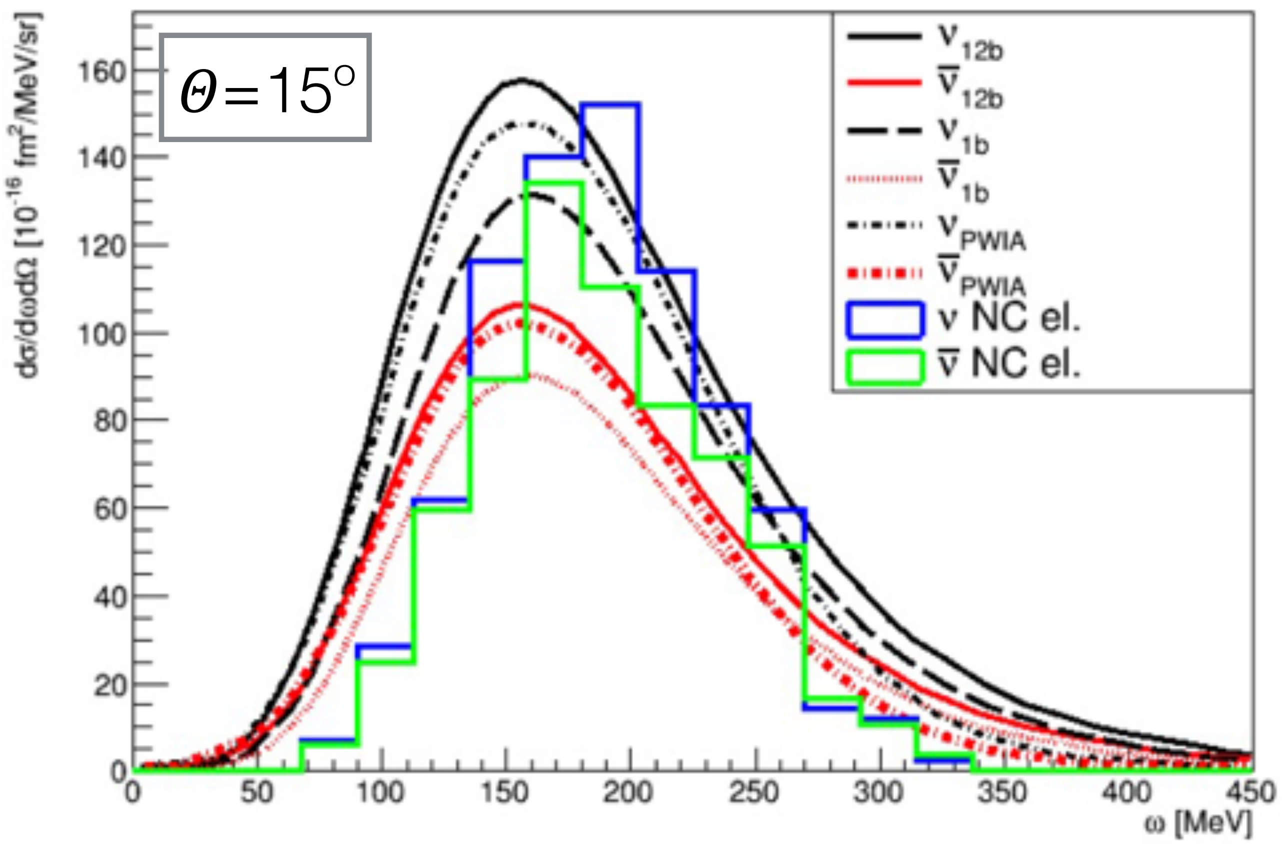


w/ G. King, F. Nunes, L. Pickering (MSU) based on discussion S. Pastore (LANL)

- Prepare GENIE generator for NC @570 MeV; would like to extend to NEUT

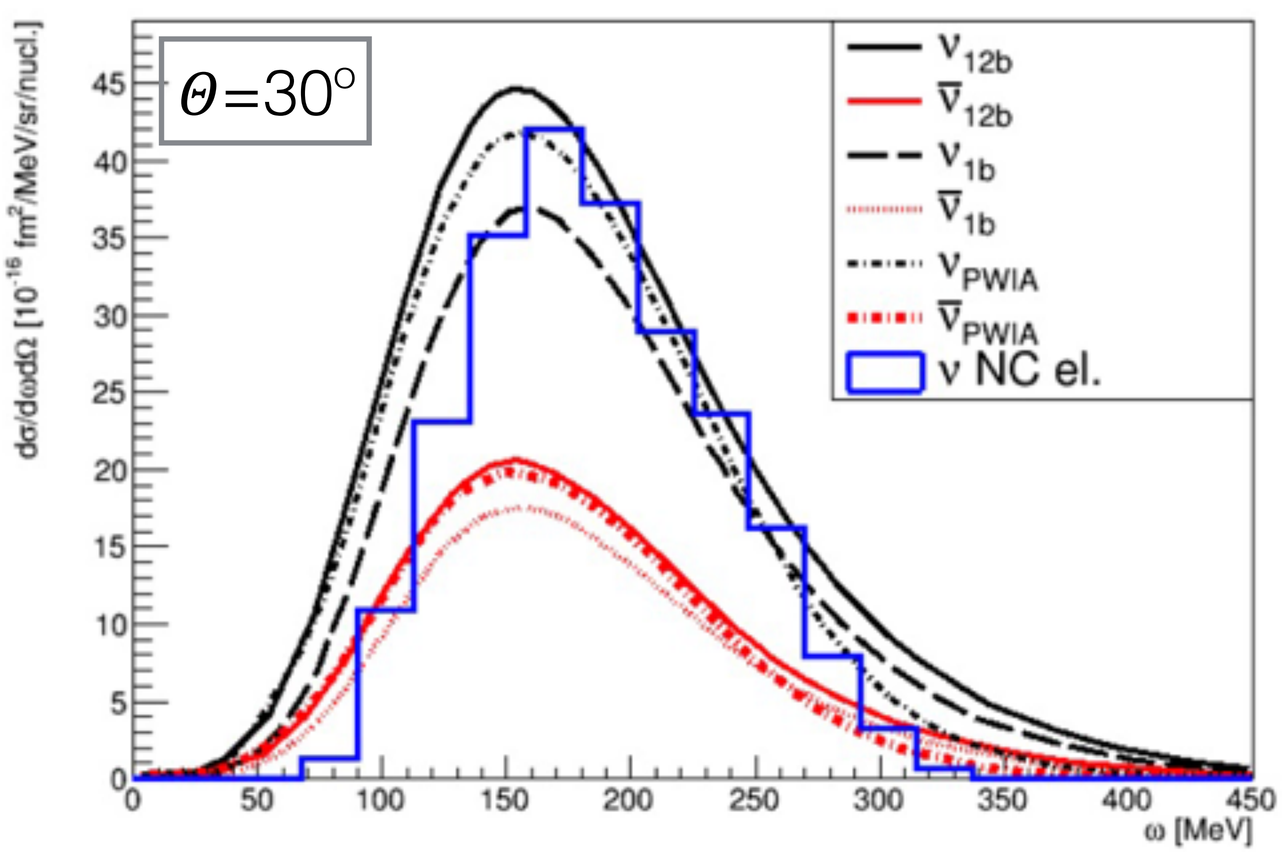
- Goals: 1) Establish common language and useful (theory) projections 2) What are the (missing) features in generators? 3) (future) What is the impact of what is missing?

Example theory+experiment idea



extremely preliminary work…

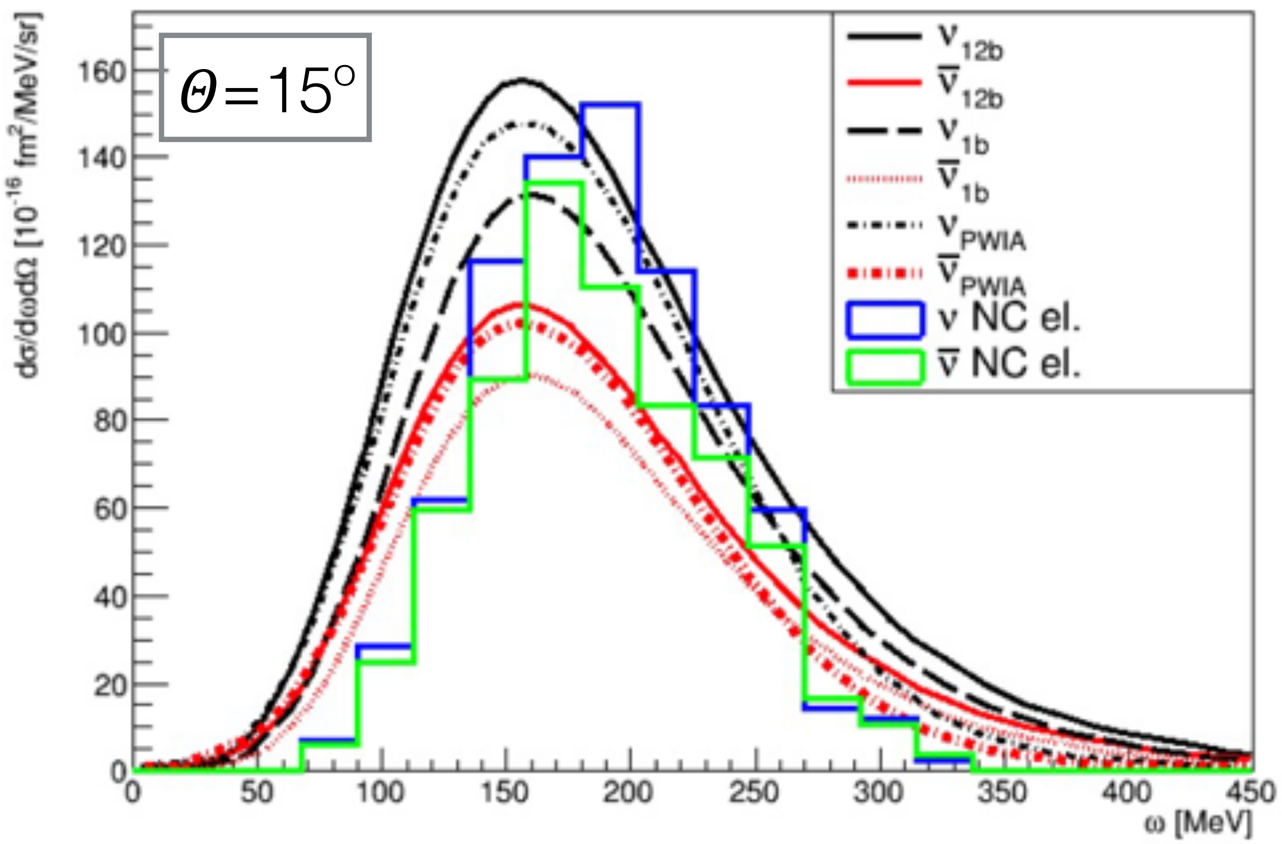
(**within the generator**) Do disagreements produce appreciable event rate differences for kinematics of interest?



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

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

Example theory+experiment idea



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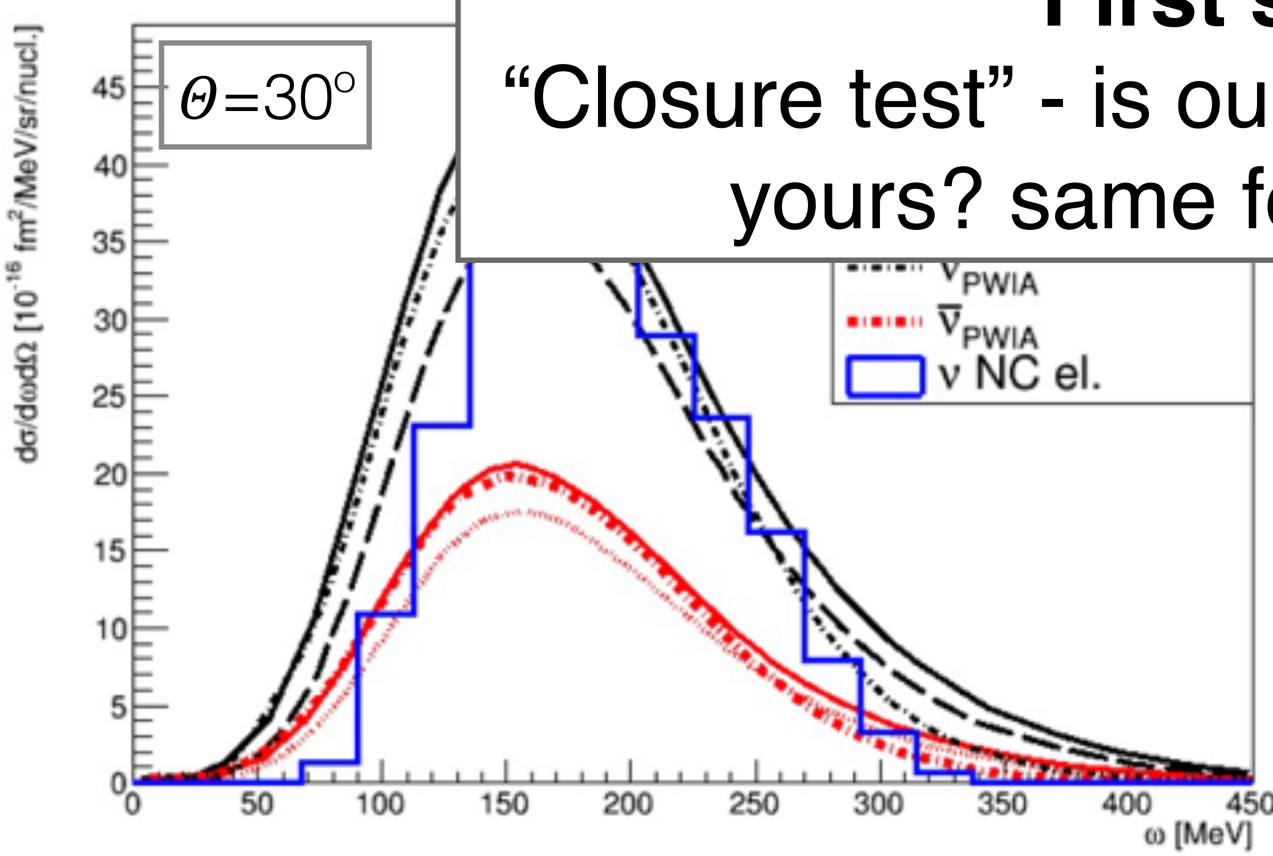
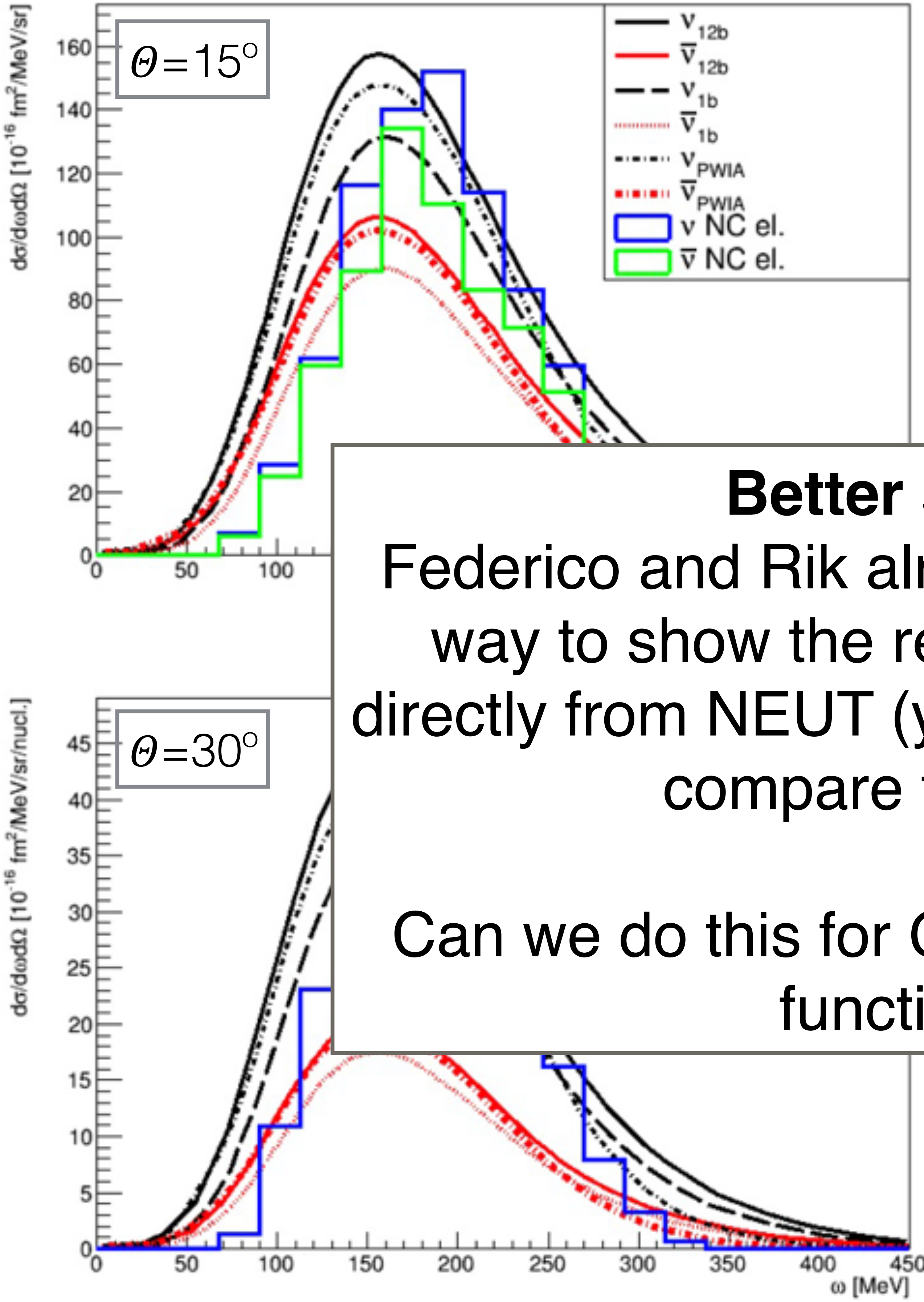


First step:
"Closure test" - is our RFG the same as yours? same for our "SF"…

(…**ry**) What physics is the model including?

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

Example theory+experiment idea



extremely preliminary work…

(**within the generator**) Do disagreements produce appreciable event rate

nematics

ry) What

odel

Better step?

Federico and Rik already figured out a way to show the response function directly from NEUT (yes?) so, we should compare that too!

Can we do this for GENIE's response function?

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

Closing thoughts

- T2K has an interactive approach to neutrino interaction uncertainties, where we:
  - Update our parameterization // test the impact tin the oscillation analysis // incorporate new theory or improved assumptions
- **What are the long standing problems? What specifically can be done to clarify, test and/or address them?**
  - Example projections (total errors, fake data studies) for impact estimation from experiment. What is useful to “users”?
  - Direct tests of generator implementation - intermediate quantities/observables can be compared to theory, escatt

Backup slides

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

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

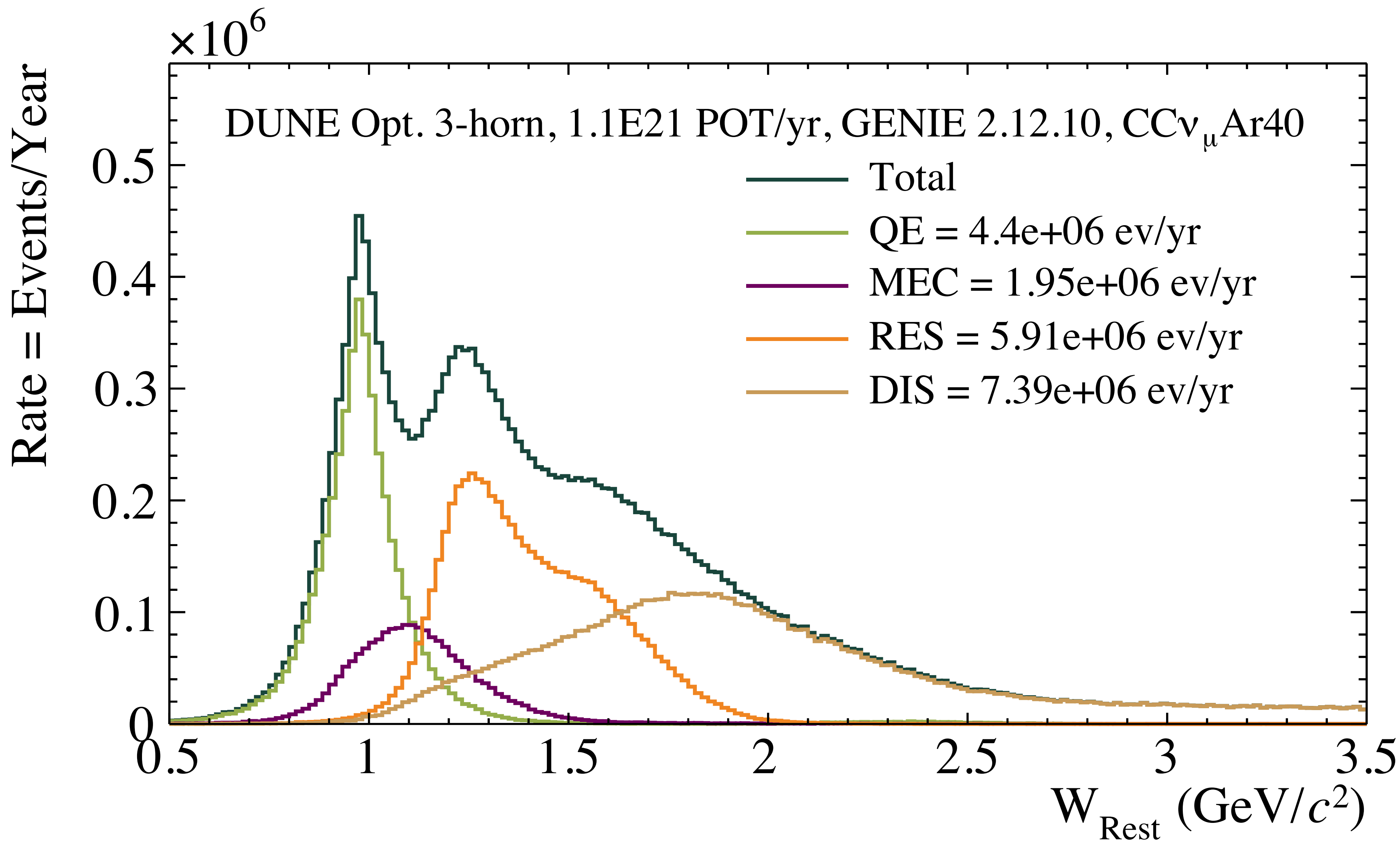
What is the role of single nucleon form factors in oscillation experiments?

- **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

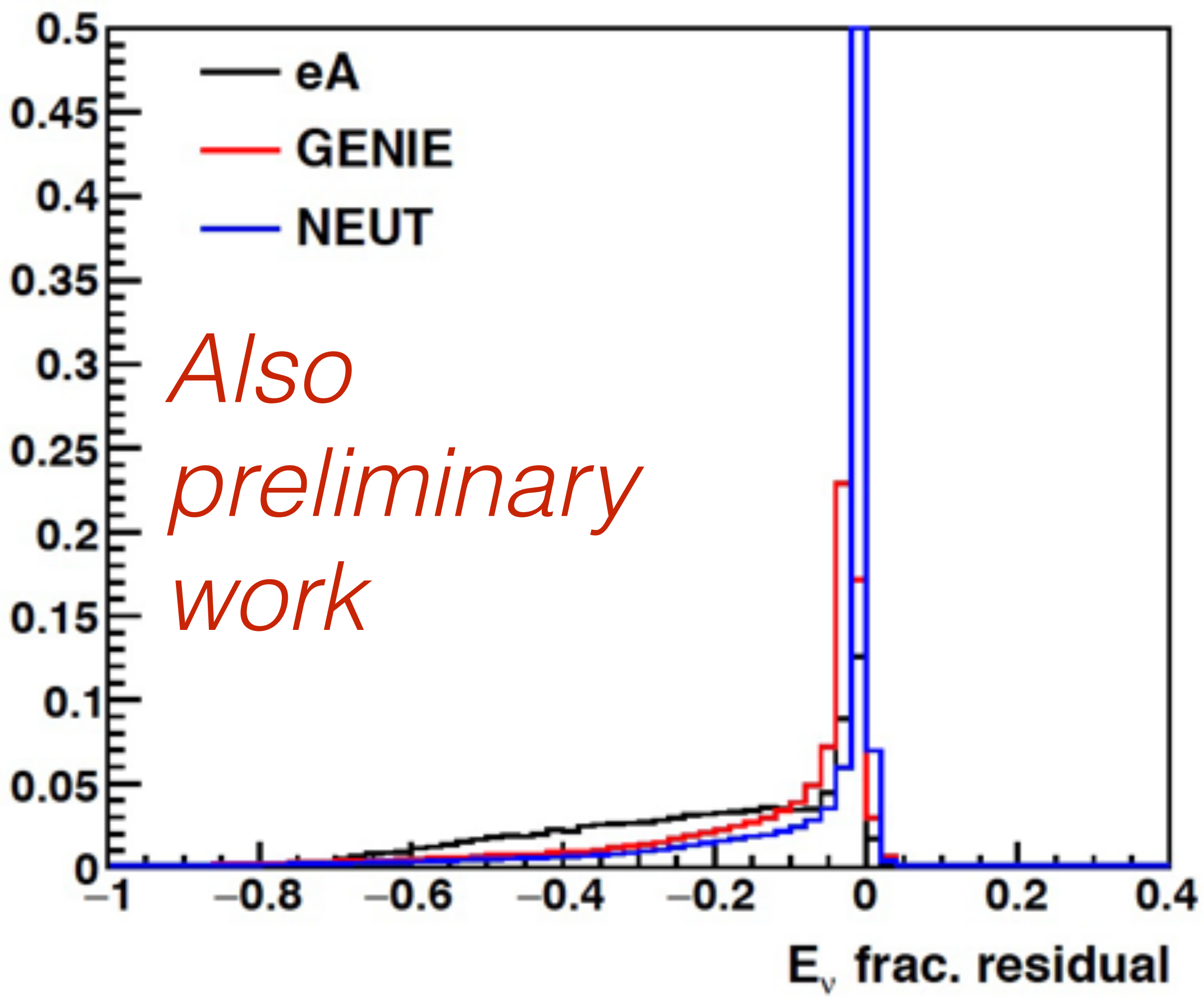
What is the role of single nucleon form factors in oscillation experiments?

- **Transition region - critical for DUNE**

- Presumably this is a necessary input?



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
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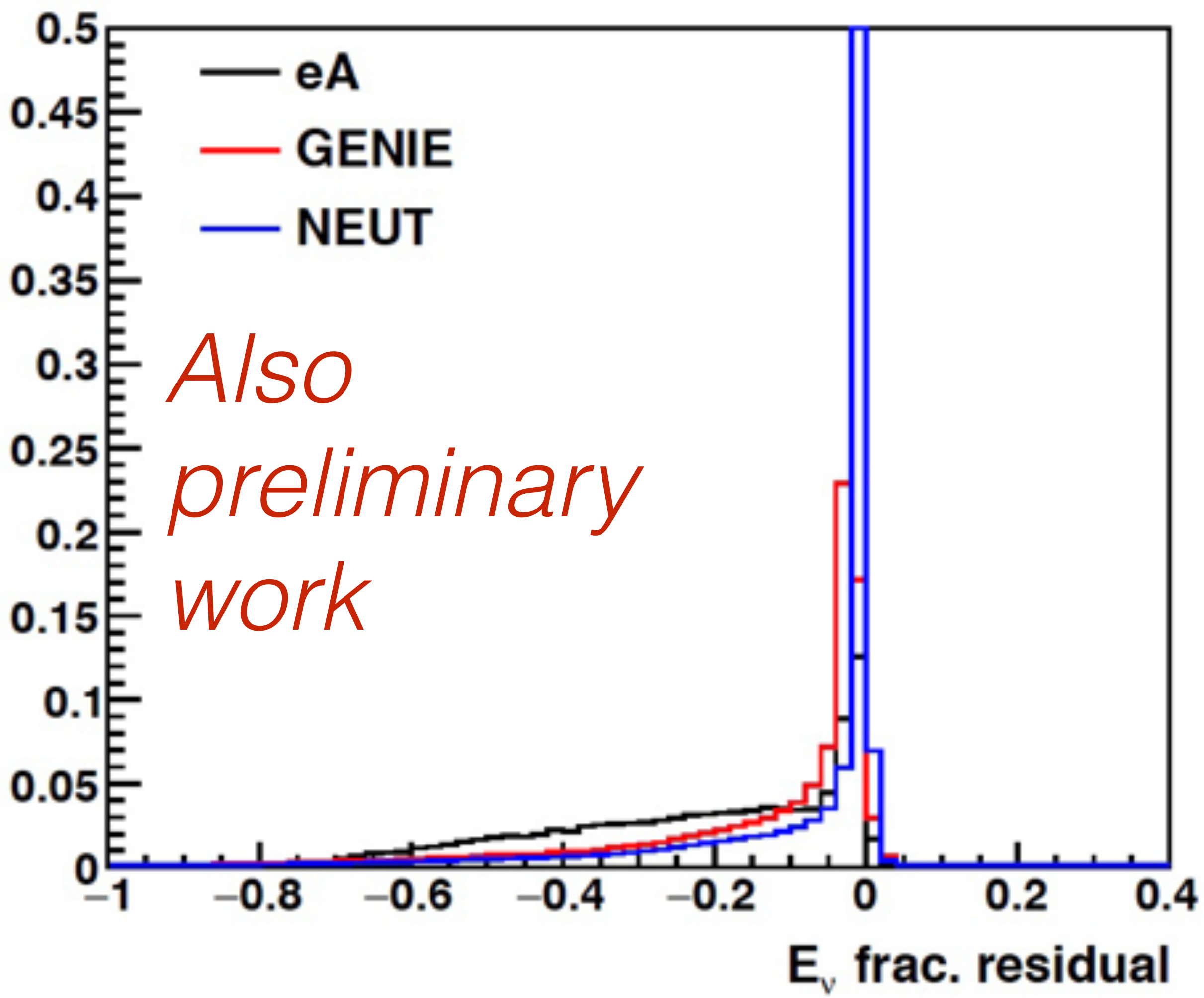

Interface success? -core projection of response function assumed in osc analysis

- Comparison of (2.2 GeV, fixed energy) electron scattering data

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

  corrections included. CC0pi signal.

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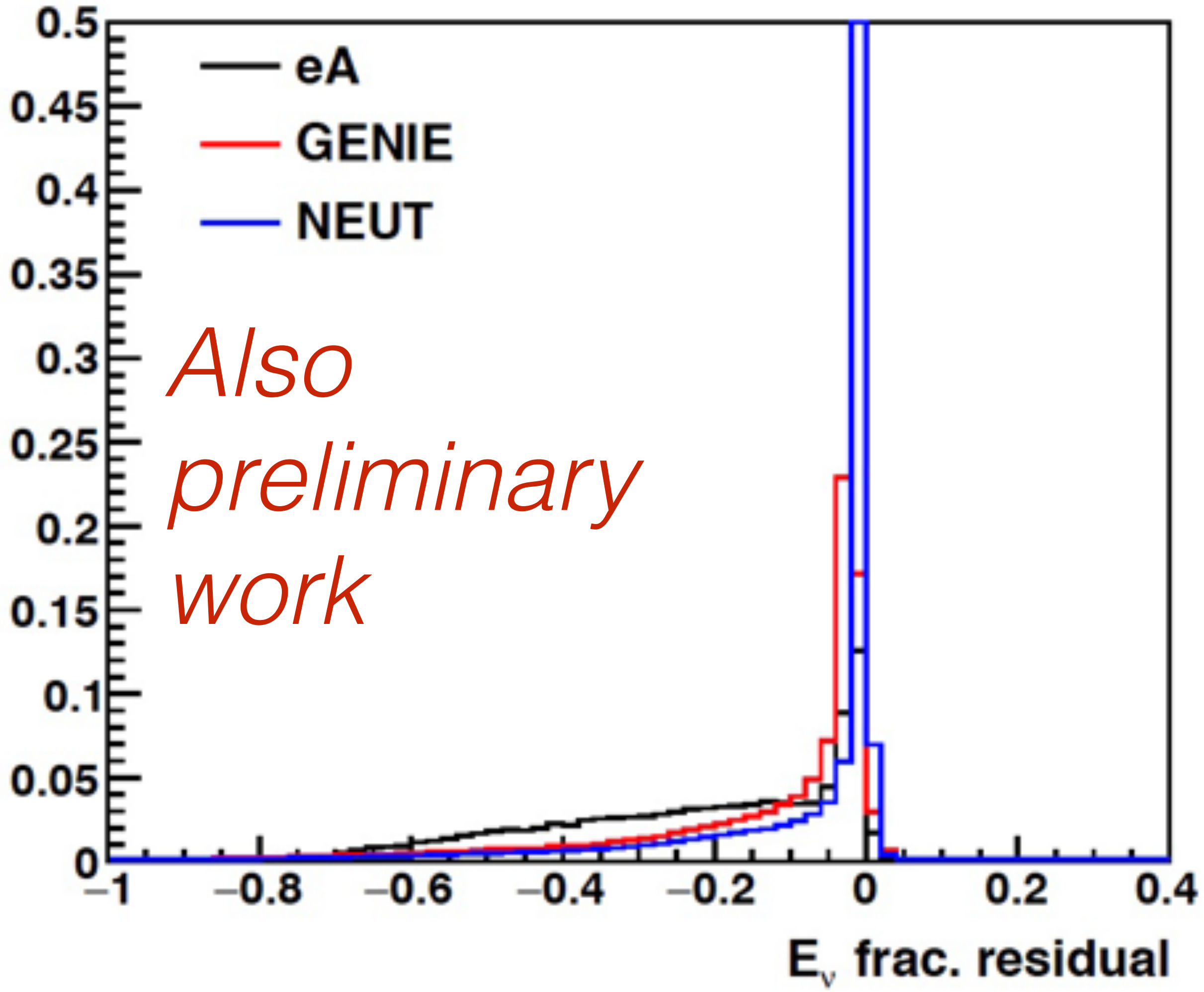
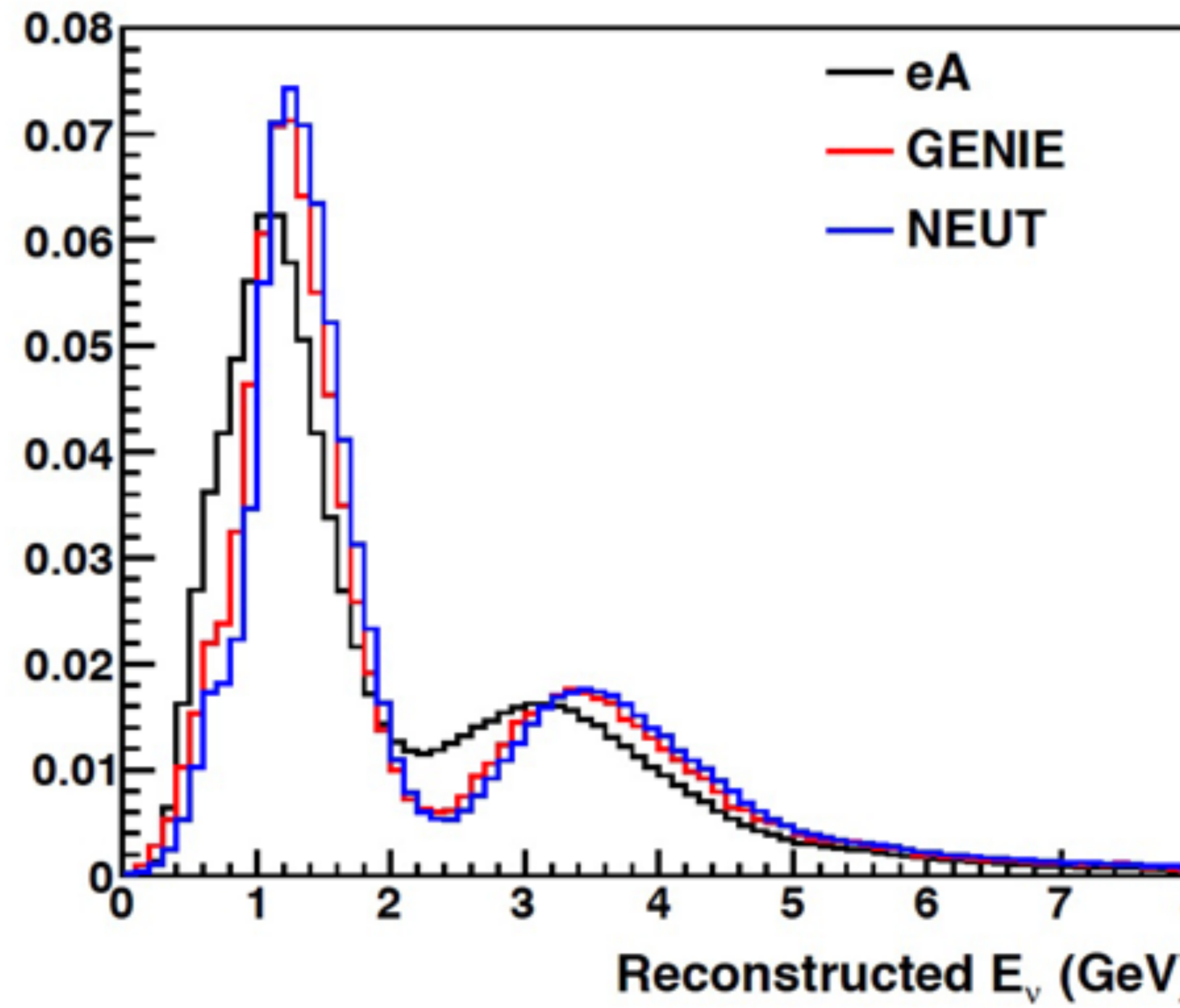
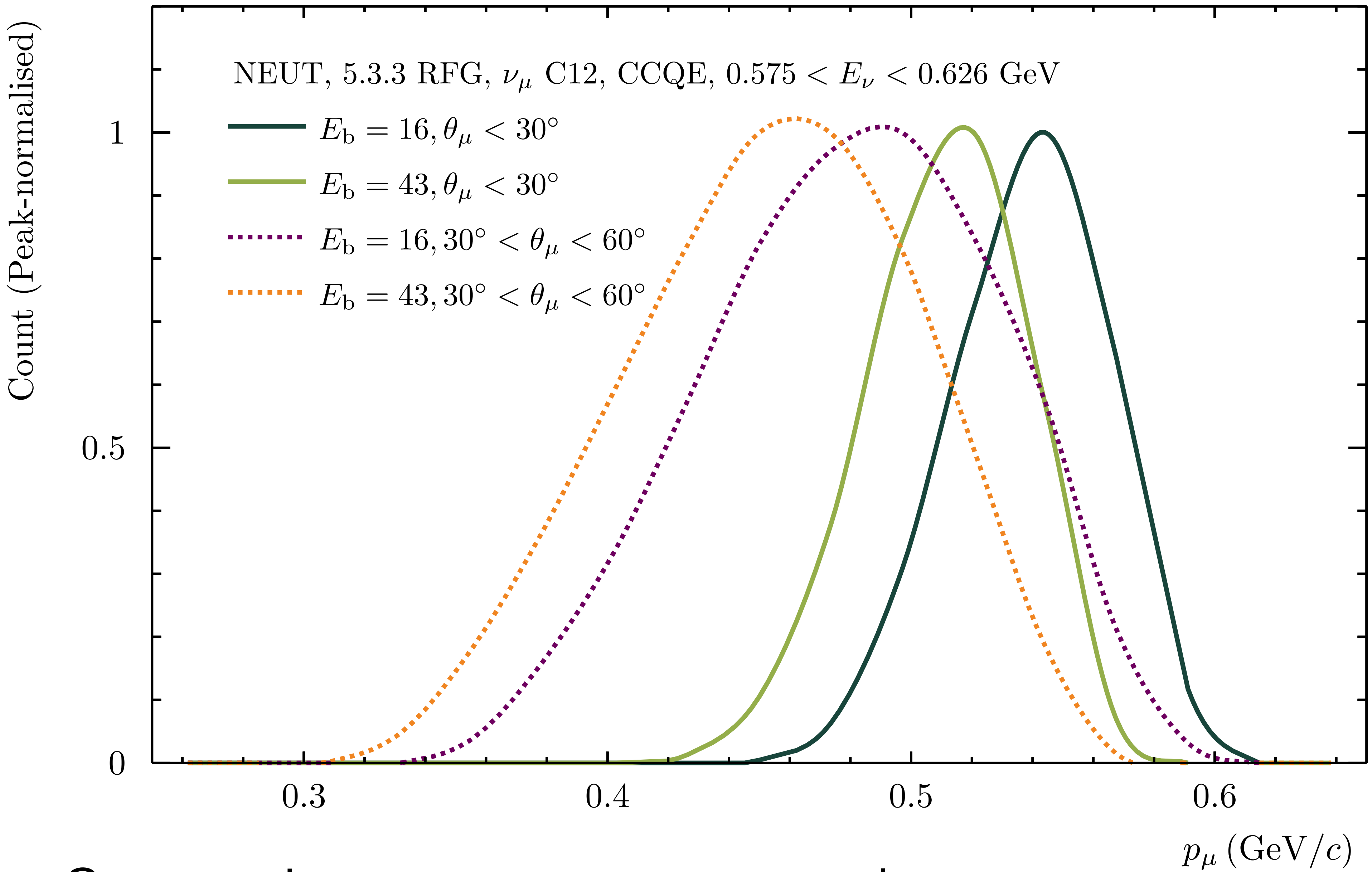




- DUNE oscillated flux; apply fractional feed down adjustment to nearby energies

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

What is this "E_b"?



Discussion in Bodek, arxiv1801.07975

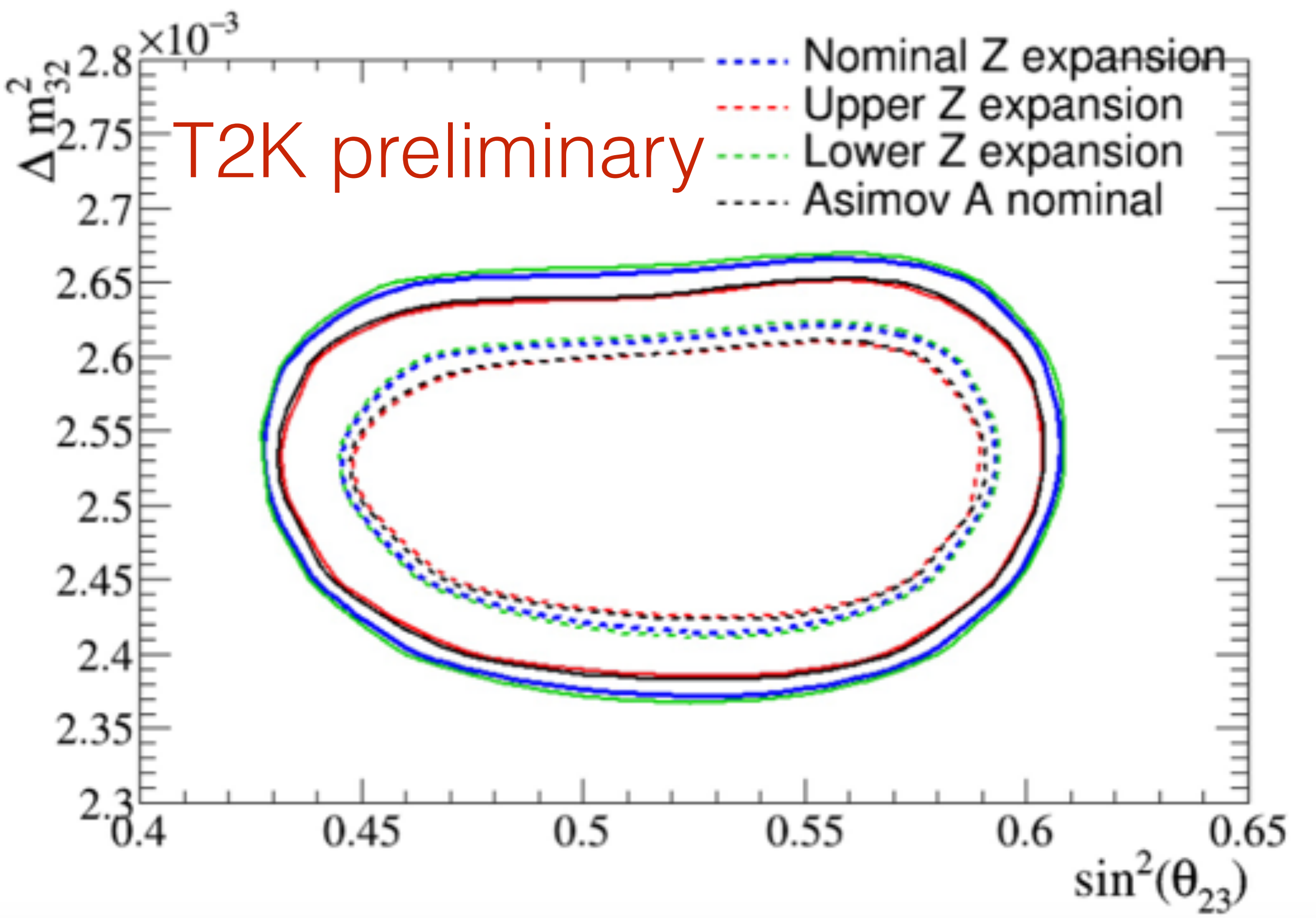
- Separation energy or removal energy
- Not really a single number, associated to a particular model
- Shifts relationship between observables (p_μ) and E_ν

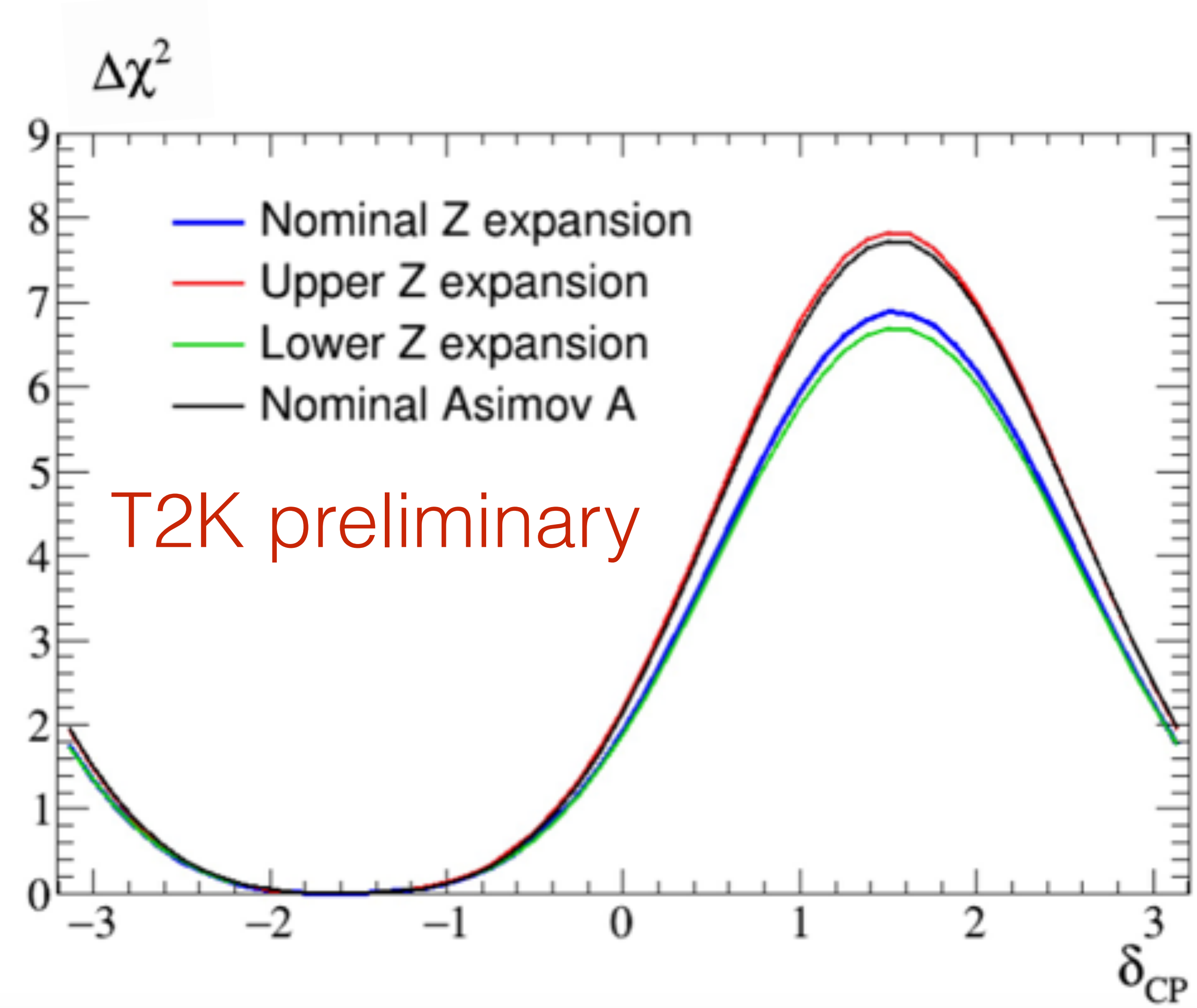
Summary: the possible issues

- 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

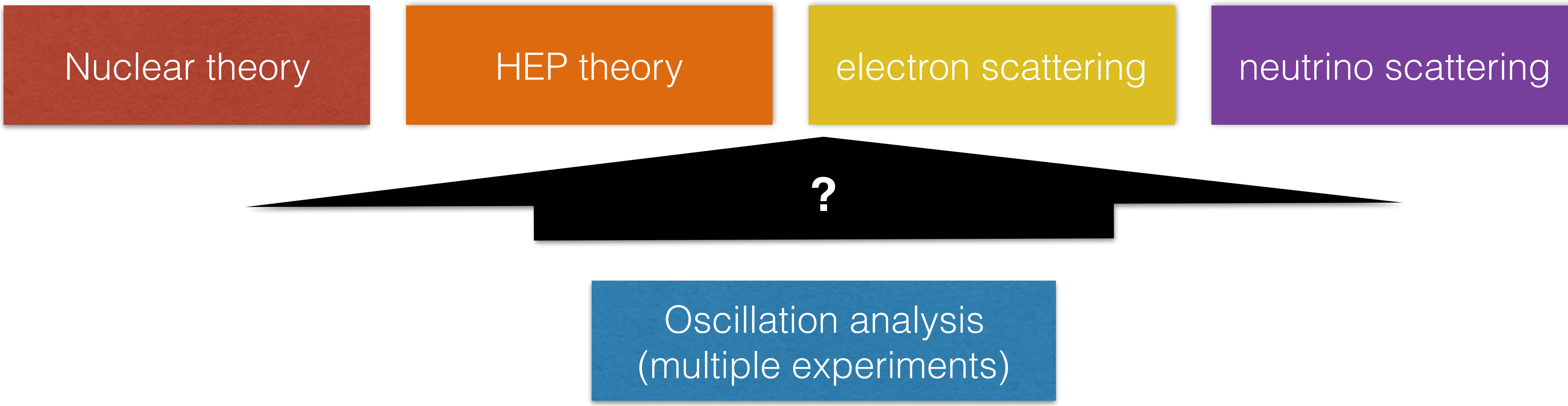
Studies on impact of alternate form factor

- Use as alternate models: “Z expansion”, 3 component fit and perform T2K analysis with current dipole model (6 fits)
- For T2K 2017 analysis, the (Q^2) nuclear model parameters compensate for mis-modeling (no bias)



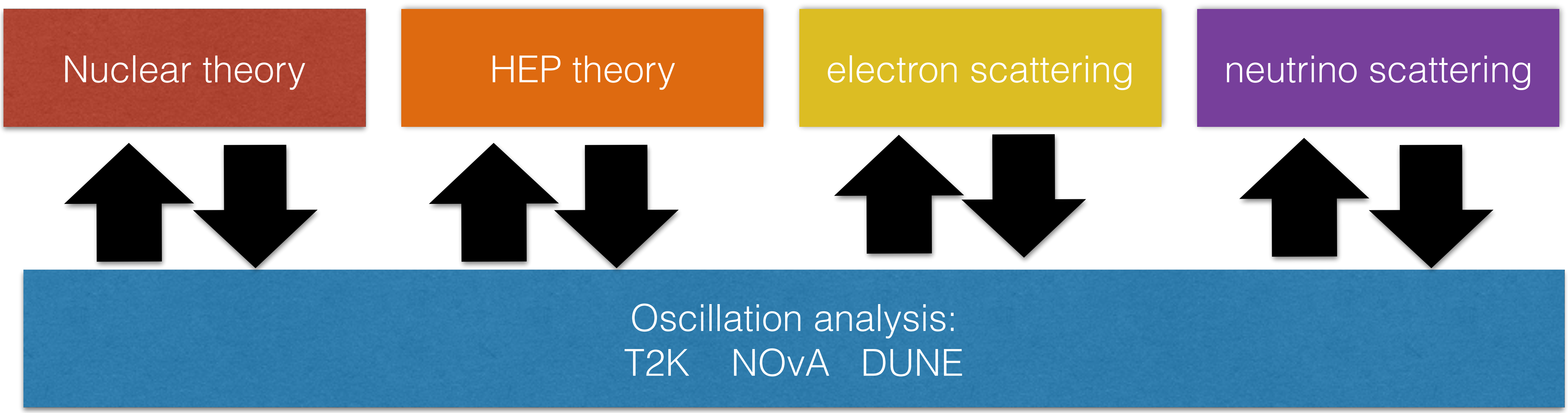


Summary: the tool kit



- **First interface:** What do we need to see out of oscillation experiments to determine what needs further study in the interaction model?

Neutrino interaction uncertainties in current (T2K) and future (T2HK) experiments



Kendall Mahn
Michigan State University

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