Neutrino interaction uncertainties in the GeV region ~~Past,~~ **Present**, and Future?

Clarence Wret

With help from: Luke Pickering (T2K, DUNE), Callum Wilkinson (T2K, DUNE), Dan Ruterbories (MINERvA), Jeremy Wolcott (NOvA), Kirsty Duffy (MicroBooNE), and years of NuSTEC, NuInt and NuFact slides

FNAL seminar
26 September 2019

Disclaimer

Impossible to know what every analysis at every experiment has done with their with interaction systematics

This talk is **broad-stroke**, using published analyses for information and examples

Let us know if you're doing something smart with your interaction systematics

And this

I will try to put clickable links like this

Archeological finds

- Many familiar names from NuInt 01 and 04

H. Budd University of Rochester	Vector and Axial Form factors applied to neutrino quasi-elastic scattering

Gallagher, Hugh
Department of Physics and Astronomy
Tufts University
Robinson Hall, Medford, MA 02155, USA
gallag@hep.umn.edu

O. Benhar INFN-Roma1	Electron/neutrino scattering on nuclei

D. Harris FNAL	Long baseline experiments with calorimetric detectors

Mann, W. Anthony
Physics Department, Tufts University
Medford, Massachusetts 02155, USA
mann@tuhep3.phy.tufts.edu

Morfin, Jorge G.
Fermilab - MS220, Batavia IL 60510, USA
jorge@fnal.gov

R. Gran Washington Univ.	K2K CC data

J.Raaf Cincinnati Univ.	MiniBooNE NC p^0 and NC elastic data

08:50		Merits/disadvantages of the existing neutrino beams (K2K, CERN, FNAL-Booster, FNAL-NuMI,....)	A. Rubbia	(ETH Zurich)	(25'+5')

Mcfarland, Kevin
University of Rochester
Dept. of Physics and Astronomy
Rochester, NY 14627-0171, USA
ksmcf@pas.rochester.edu

J.Nieves Granada Univ.	Nuclear many-body theory of electroweak interactions with nuclei

- <u>**Excellent**</u> job security in neutrino interaction physics!
- (also a great few afternoons' read!)

Archeological finds

and I had just turned 10...

Neutrino oscillation primer

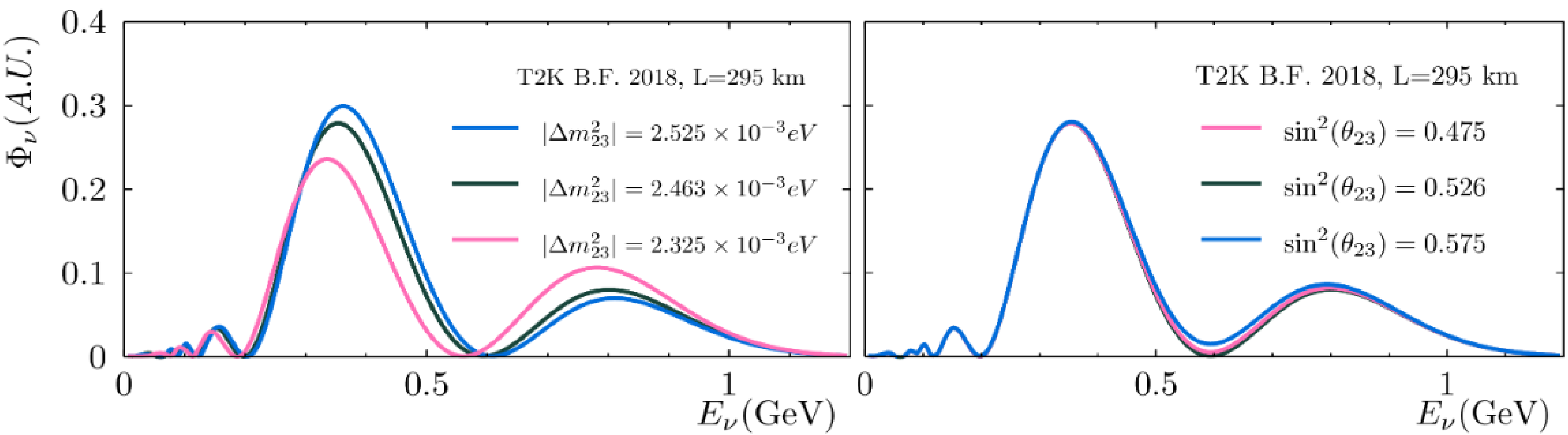
Why are we even here?

Neutrino oscillation primer

- Neutrino oscillations have E_ν dependence

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{\boxed{E}}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

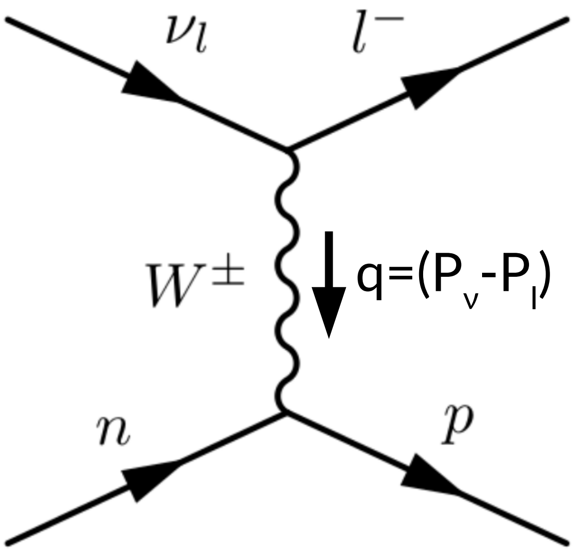
- Shift in amplitude biases θ, shift in frequency biases Δm^2



- Possible to mistake a systematic causing a shift as an oscillation parameter value

Neutrino interaction 101

This is a neutrino interacting through CCQE on a **nucleon**

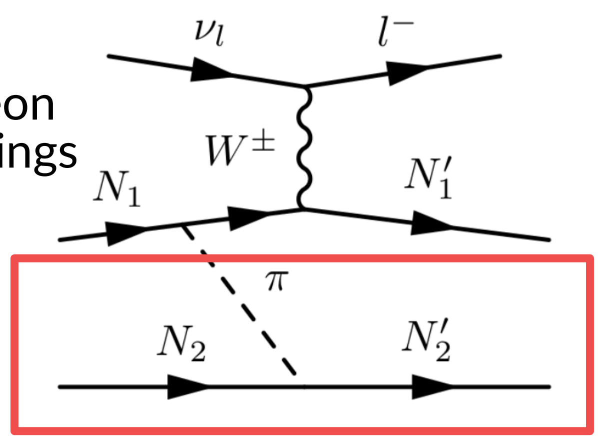


Define kinematic variables

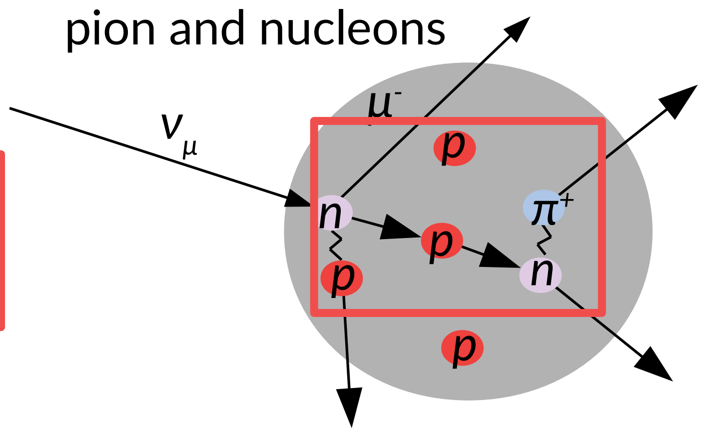
e.g.
$Q^2 = -q^2 = -(P_\nu - P_l)$ (four vectors)
$q_0 = E_\nu - E_l$
$\mathbf{q}_3 = \mathbf{p}_\nu - \mathbf{p}_l$
$W^2 = (P_n + q)^2$

This "clear picture" get's muddled up in the **nucleus,** for example

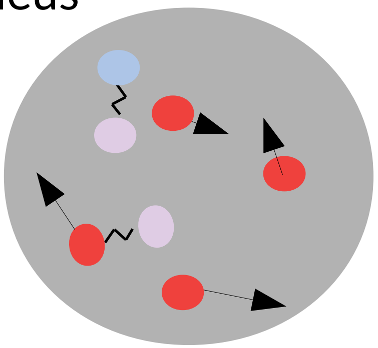
Nucleon couplings



Final state interactions of pion and nucleons

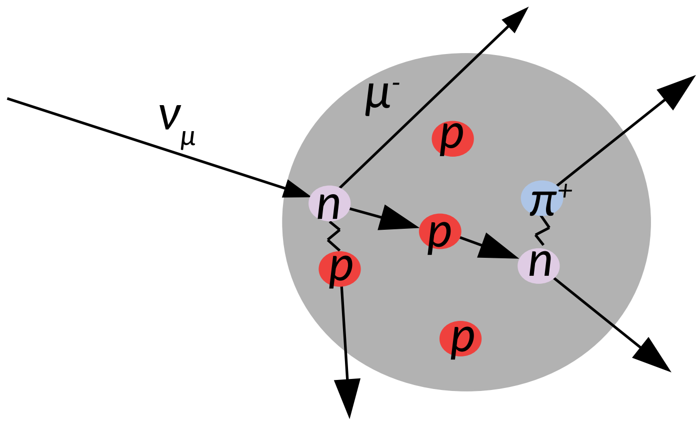


Initial state motion of the nucleons in a nucleus



Neutrino oscillation primer

- Reconstructing E_ν **perfectly** means reconstructing all the primary particles **and** the struck initial state
  - Even DUNE can't do this!



$E_\nu^{Reco} = E_p + E_{\pi+} + E_n$

Classify true CC2p2h as CC1π^+1p

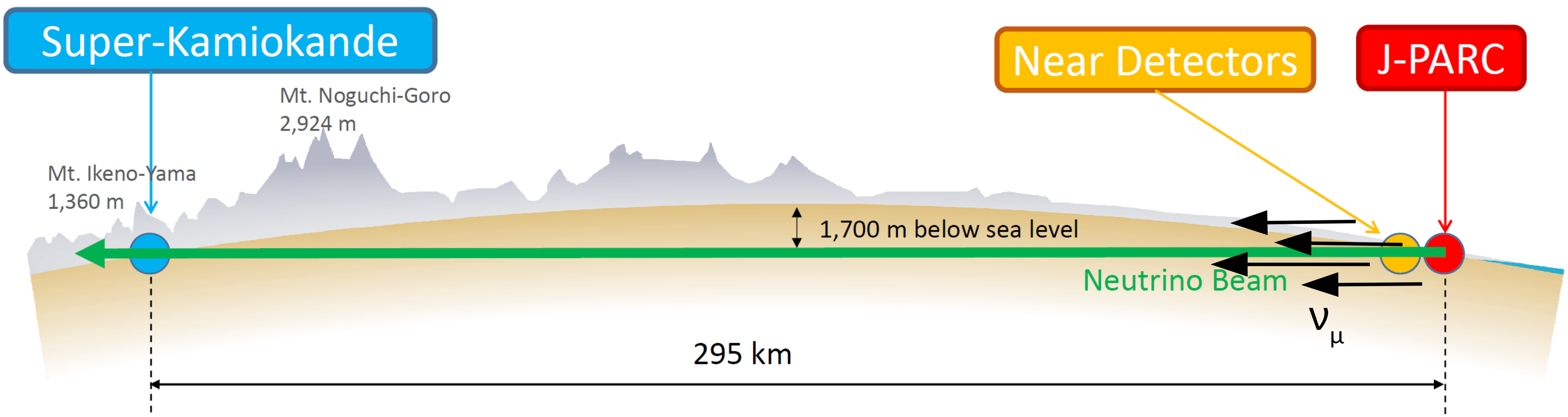
Not the easiest to spot

If $E_\nu^{Reco} = E_\mu + E_{had}$ still missing $E_{initial\ n}$

- **Always** rely on some mapping of "Observed final state in detector" to "Incident neutrino energy"
  - Fine to misreconstruct, as long as the effects are well modelled and accounted for
  - Appropriate systematics to mapping is crucial to unbiased estimation of oscillation parameters

Long baseline neutrino oscillations

- Often use near-detector to constrain systematics "before oscillations"



- Rate at both detectors have common ingredients

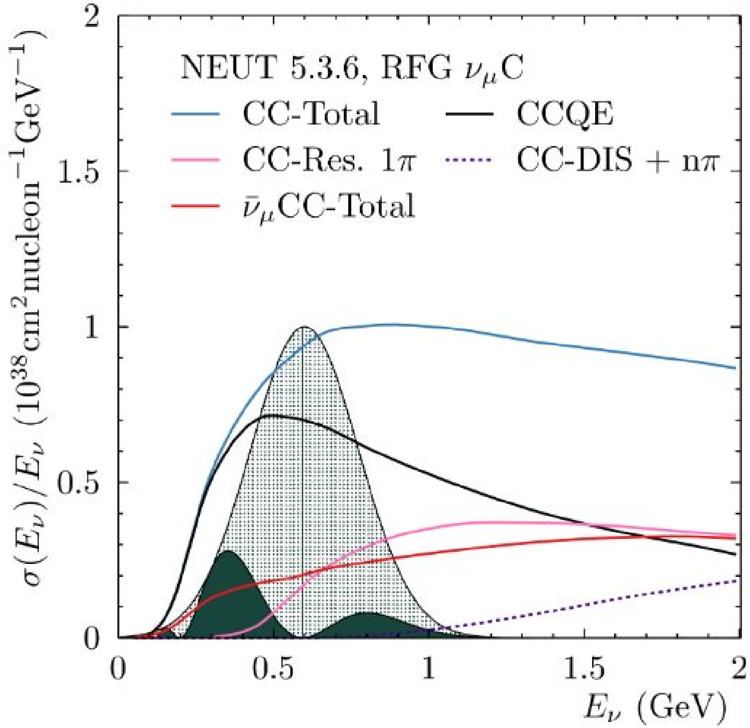
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\Phi(E_\nu) \times \boxed{\sigma(E_\nu, \vec{\mathbf{x}})} \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \rightarrow \nu_B)}_{\text{Far}}$$

- Everything happily cancels… right?

L. Pickering NuFact2019

Why things don't cancel

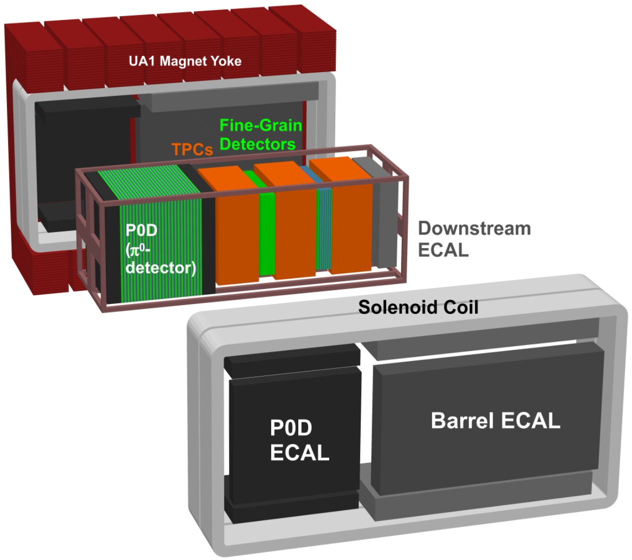
- Targets: T2K CH at ND280, H_2O at SK
  - Need to model how $\sigma_{CH} \sim \sigma_{H2O}$
- E_ν spectrum: Oscillations, and beam spread
  - Changes relative importance of the contributions to $\sigma(E_\nu)$



  - Collect most ND statistics at the peak of the event rate, often coinciding with the minimum event rate at the FD

Why things don't cancel

- Detector geometry and acceptance differences



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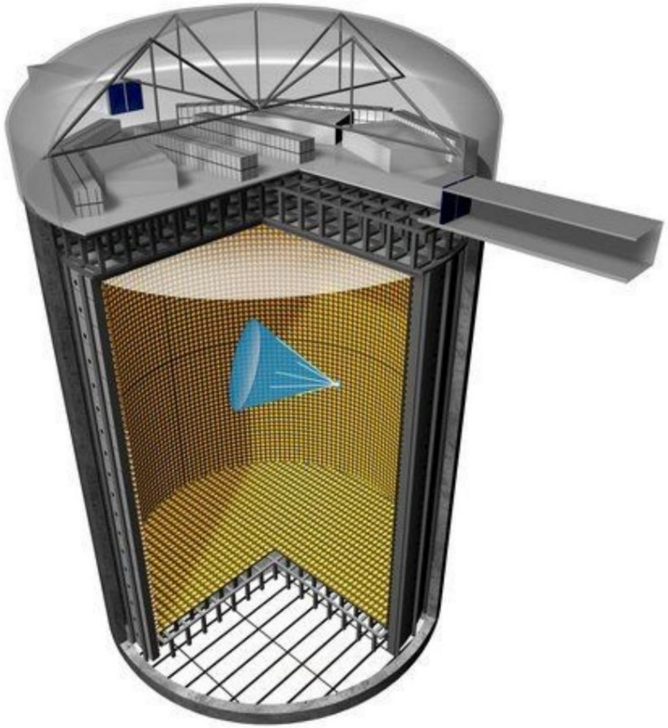
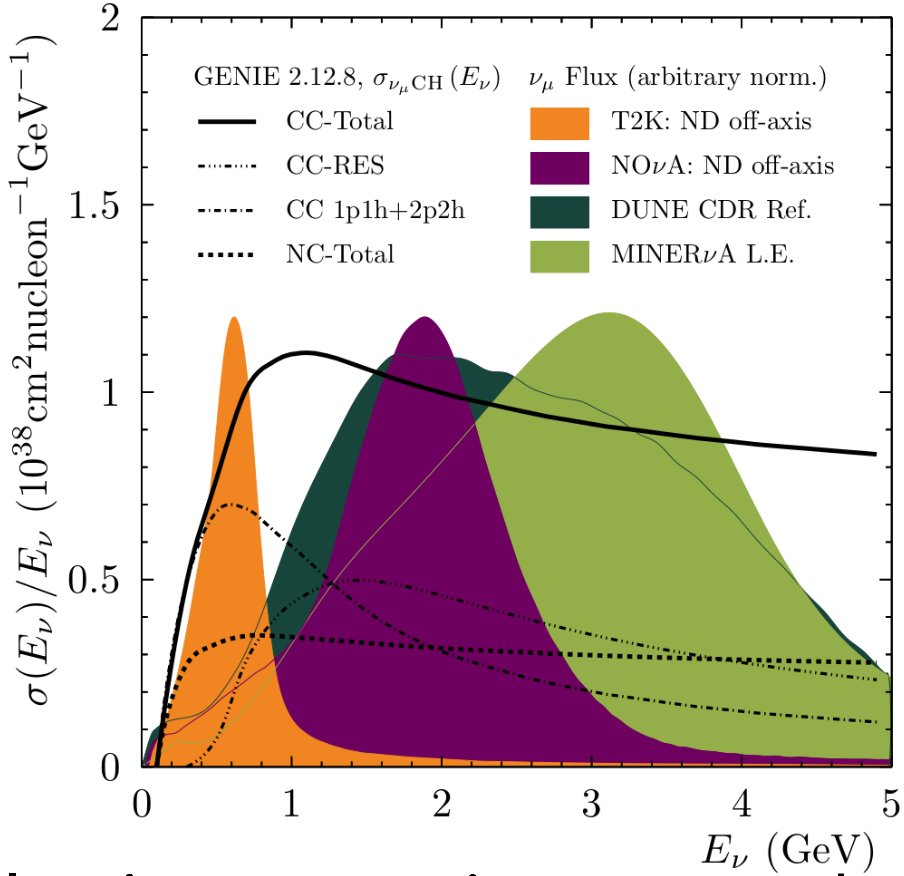


- Selection at the ND tunes the model to forward-going events, whereas FD has full acceptance
  - Or you might have a smaller ND than FD, leading to different acceptance
- Rely on flavour modelling: collect predominantly ν_μ events at the ND, but what about ν_e and anti-ν?

Experiment landscape

- Generally, oscillation experiments choose E_ν range to match L/E_ν for maximum ν_e appearance



Micro/ MiniBooNE roughly at T2K energies, sorry!

- Coupled with selections, experiments emphasise different regions of neutrino interactions
  - e.g. T2K CC0π; NOvA CC0π, CC1π; DUNE/MINERvA everything

L. Pickering NuFact2019

Our beloved generators

Our beloved generators

- GENIE, NEUT, NuWro and GiBUU*
- Generally we're told
  - GENIE is the experimentalists generator
  - NuWro is the theory-driven generator
  - GiBUU is the nature
  - NEUT is for T2K/SK/HK
- In the eye of the experimentalist, GENIE and NEUT have advantage of event by event reweighting
  - Makes evaluating (some) cross-section systematics easy (not necessarily sufficient though!)
  - NuWro is working on it
- GENIE and NEUT provide "default uncertainties" to experiments

*There are others (e.g. NUANCE, FLUKA/NUNDIS, NeuGen)

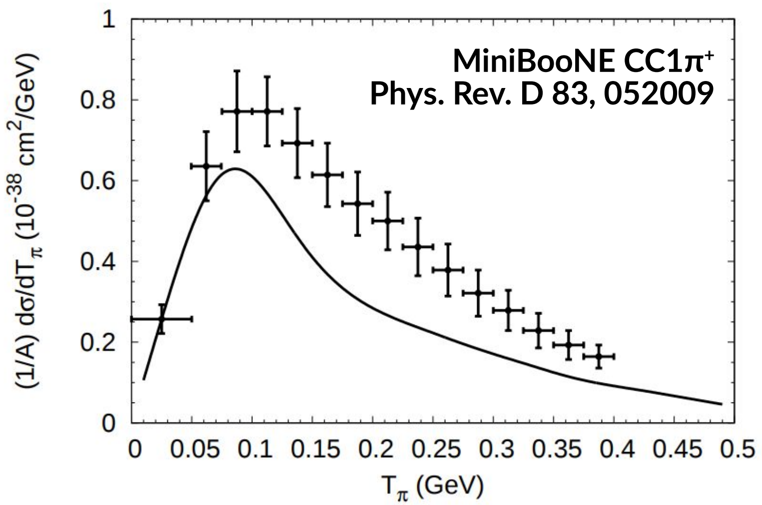
Our beloved generators

- I'm inclined to disagree with the earlier statements

> ◻ *Now NEUT is not only for SK,K2K,SB, and T2K*
> *We hope NEUT is used in a lot of experiments*

Mitsuka-san, NuInt07

- NuWro has geometry and flux drivers, GiBUU is able to
- ...and GiBUU fails to describe MiniBooNE CC1π^+ (not nature?)



- Detail the strengths of each generator: what do they say about your measurement and your chosen systematics?

Where are generator uncertainties from?

- One of my favourite talks, Hugh Gallagher at NuTune2016
  - Details the history of NUANCE→NeuGen→GENIE modelling and uncertainties, the struggles, and the thought process

- Similar story for NEUT and NuWro

Where are generator uncertainties from?

Problem: Nucleon vs. Nucleus

The discussions about the size of these uncertainties took a significant amount of time.

Realization that our simple models might not be able to account for observations on nuclei.

(M_A from K2K, MiniBooNE, …)

A gradual move towards accepting the role of neugen3 as an "effective model", and that our overall systematic error treatment should account for real physics *absent* from our model.

Mechanically, errors handled through free nucleon parameters - therefore inflate these uncertainties to account for what we might be missing.

NUTUNE 2016 H. Gallagher, July 12, 2016 24

Where are generator uncertainties from?

Lessons Learned [4]

Again: value in having deep expertise with the external data.

Again: advantage of reweightable approaches.

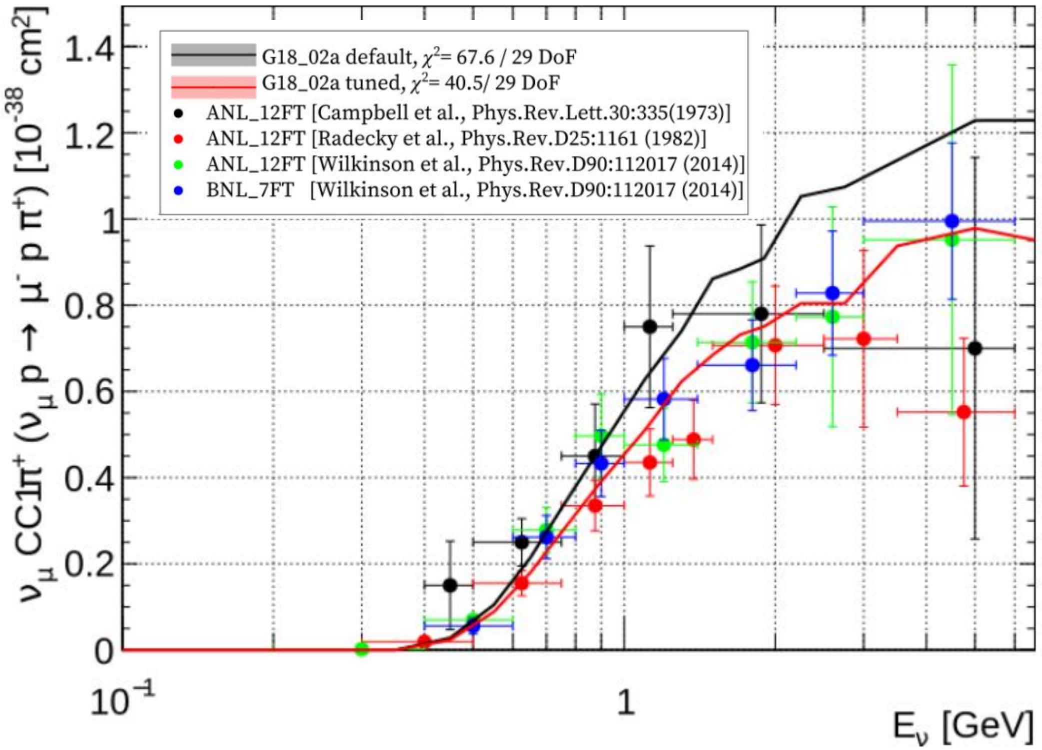
Question of relevant systematics was driven by physics objectives (numu CC disappearance). Analysis specific, not generic!

Understanding the details of the model (in particular, assumptions), were very valuable in thinking about sources of uncertainty.

NUTUNE 2016 H. Gallagher, July 12, 2016 41

Where are generator uncertainties from?

- GENIE has recently revisited their tunes for v3
- For example, single pion model updated to account for more realistic theory
  - Lepton mass effects via Berger Sehgal
  - Tuning of the axial form factors



- But no detailed nuclear systematics → Up to experiments

J T Vidal, NuInt18

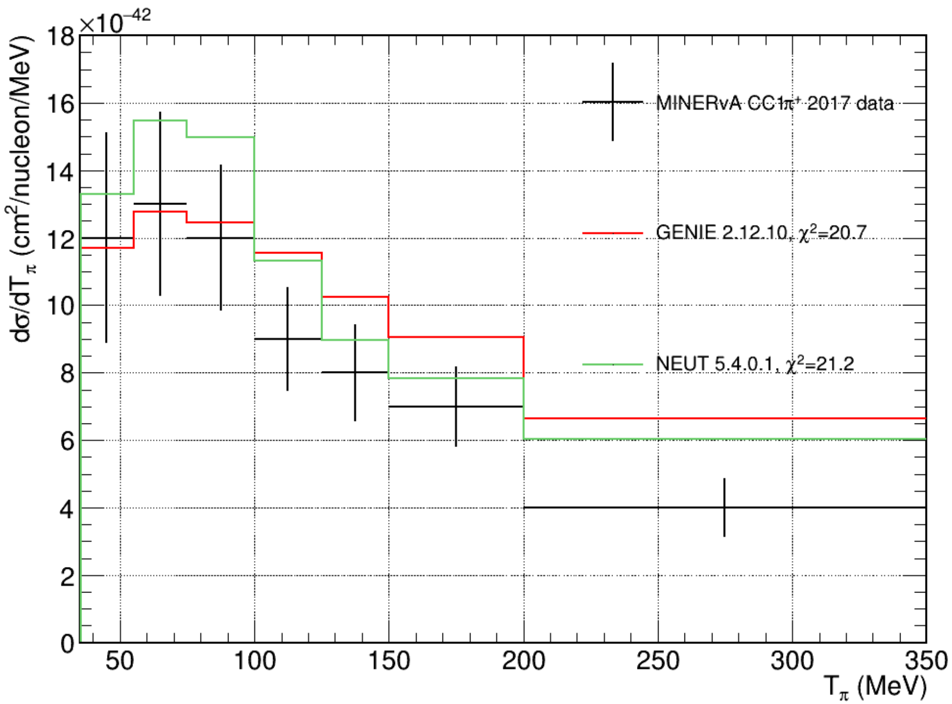
General take-home message

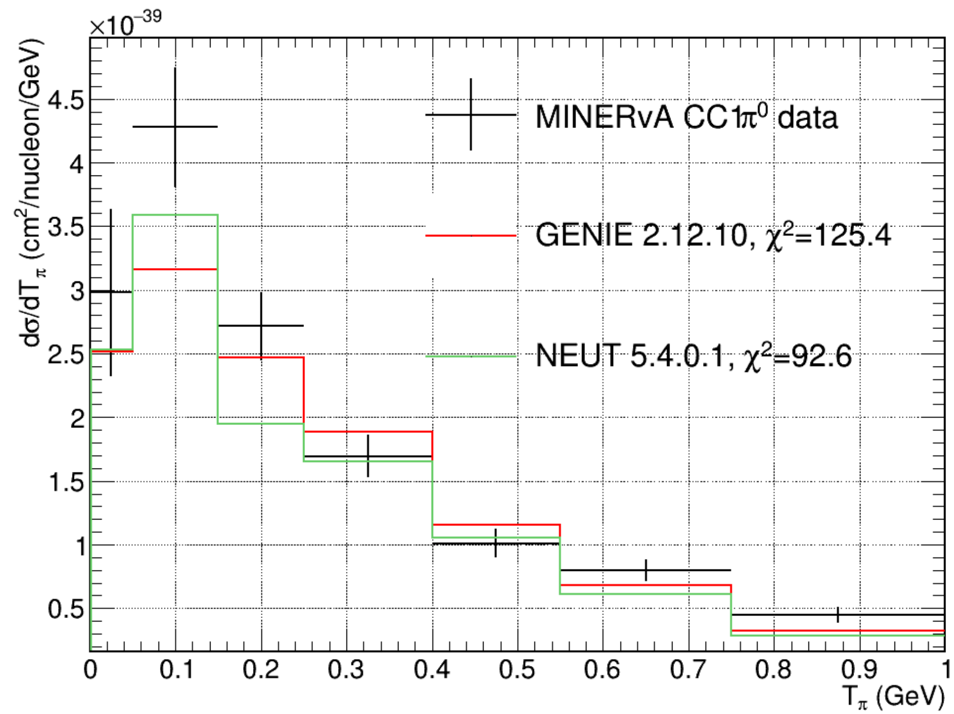
- Generators don't necessarily describe data, although **maybe** just about covers it with systematics
  - Inflate errors to "cover" **existing data** is common practice
- But is this enough for your measurement?
- If you're doing a novel measurement where there is no previous data, you must **find inspiration further afield**
- Deeper understanding of the **model and external data** is critical

What do experiments do?

What do experiments do?

- GENIE/NEUT 1σ to estimate uncertainties
  - What does 1σ mean for your measurement?

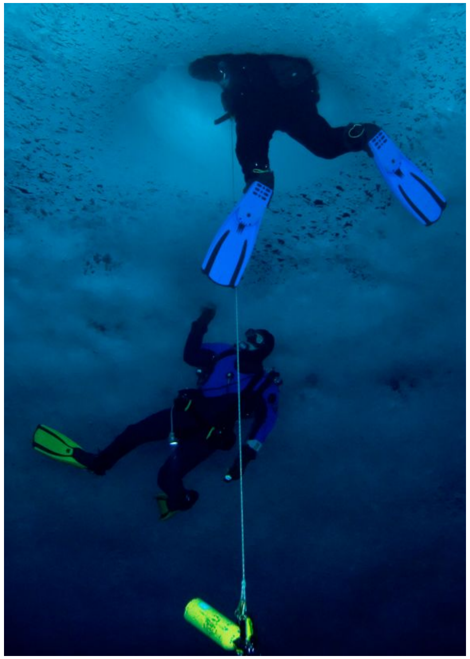




- GENIE does pretty well estimating the CC1π^+ cross-section, but not so well with the CC1π^0 cross-section
  - Also, pion shape often worse than muon shape
  - Should we revisit generators' 1σ? Yes, most likely!

What do experiments do?

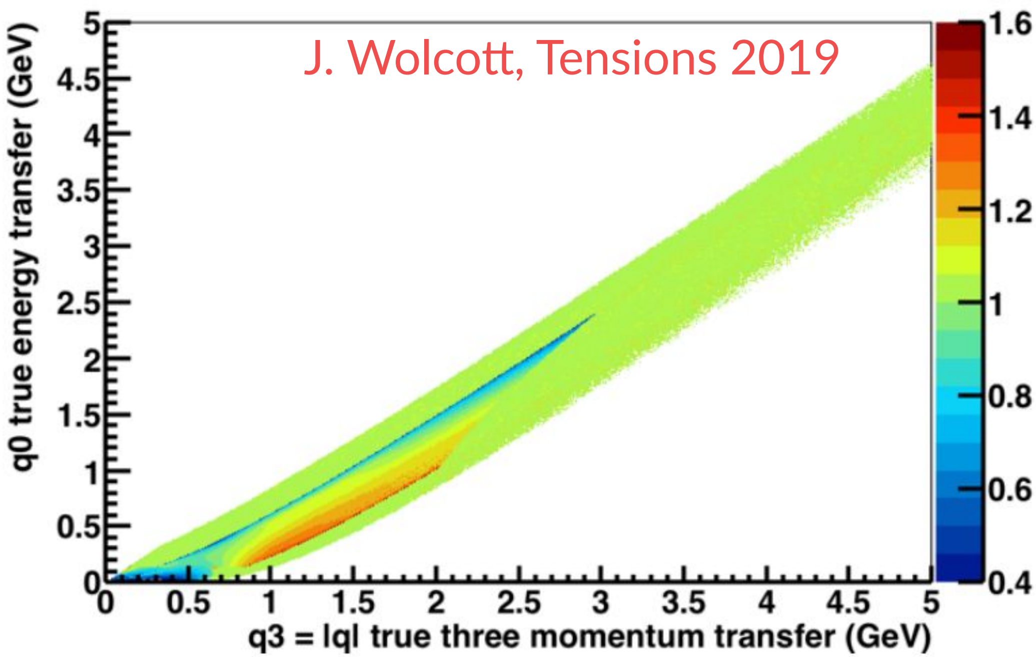
- Community provides parameterisation of some effects, e.g.
  - "RikRPA": suppresses CCQE at low Q^2
  - GENIE 1π fit GENIE parameters to ANL/BNL data
  - GENIE 1π low Q2 suppression from MINERvA data
- Develop "in-house" experiment specific models
  - MINERvA 2p2h tune
  - NOvA, T2K and DUNE interaction model

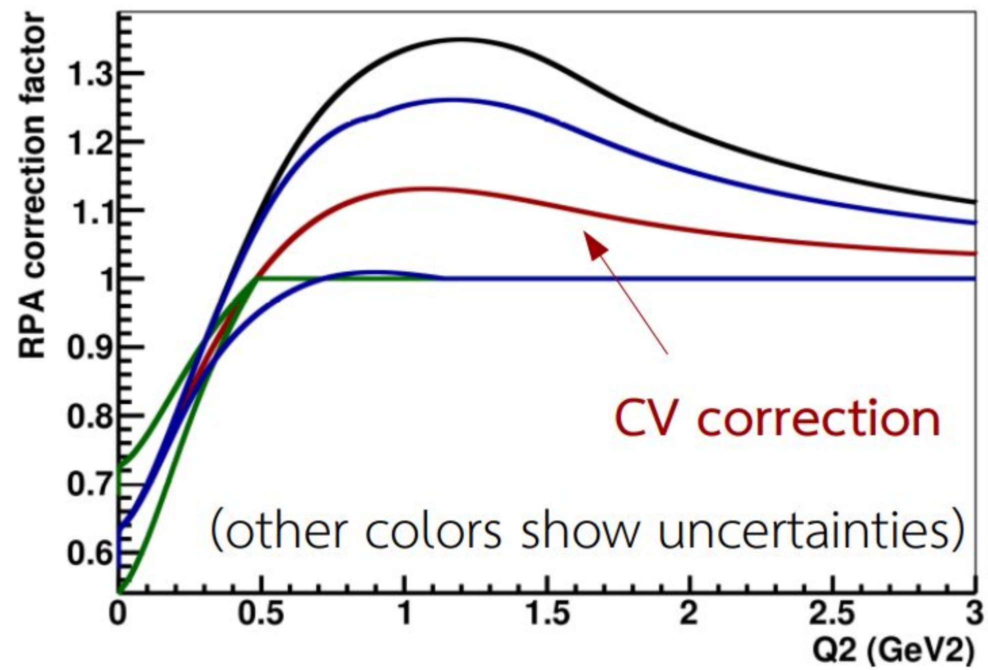


Let's dive into the literature!

RikRPA

- Suppresses low Q² GENIE events to match Nieves 1p1h
  - Aimed to collect both effect of LFG and of RPA
  - Large (40%) suppression at $Q^2 \to 0$





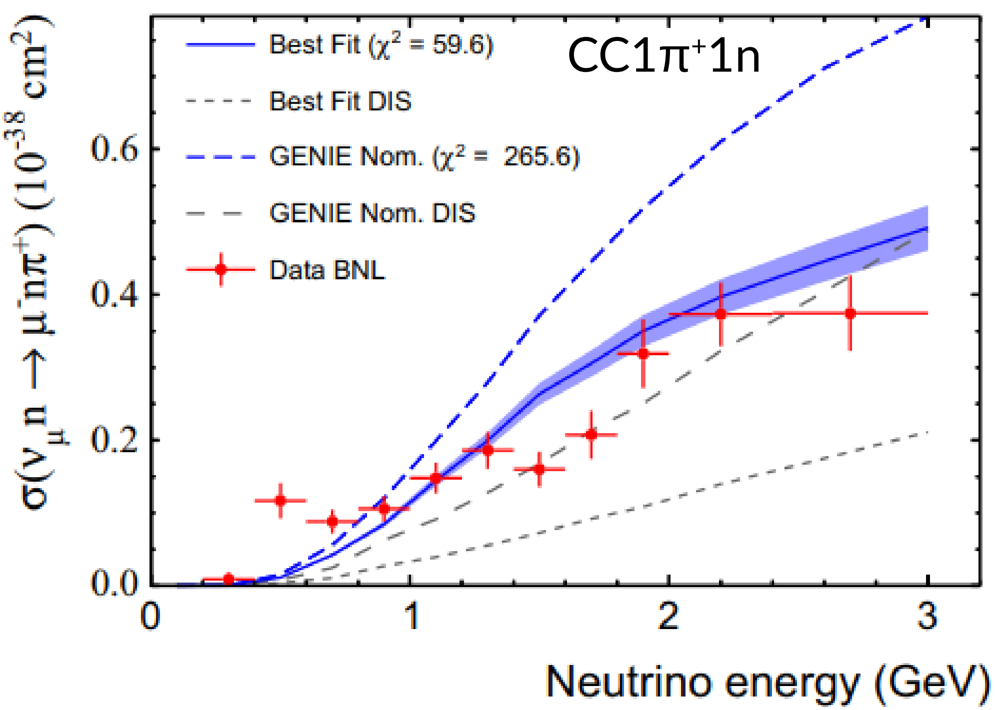
- Effect observed in e-A scattering, most likely in MiniBooNE CCQE data, and in MINERvA CCQE and CC-inclusive

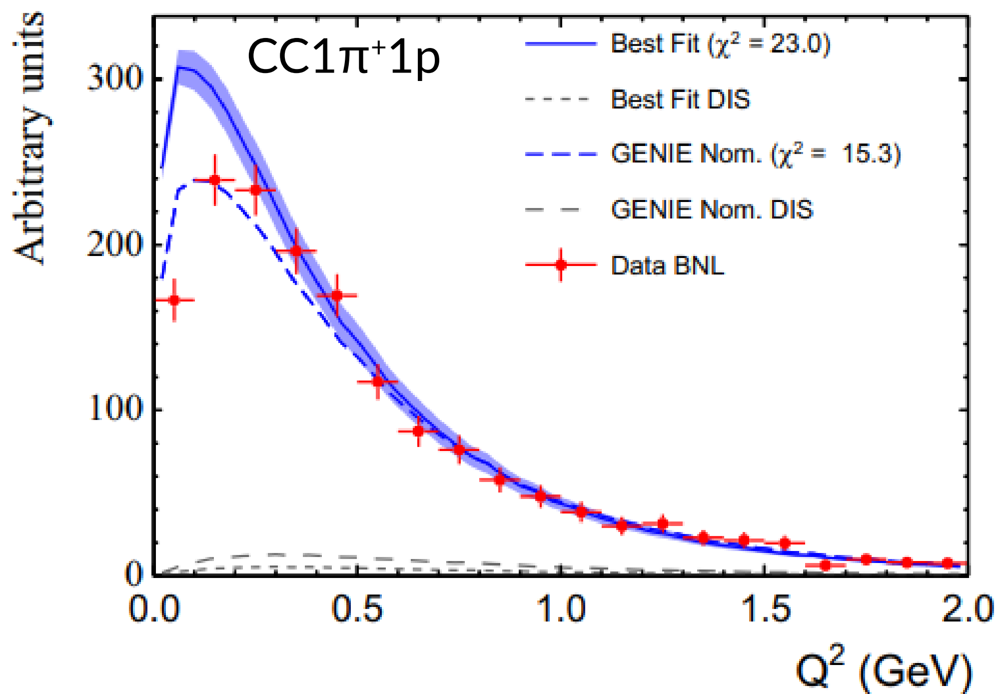
Nieves et al

R. Gran, arxiv

Single pion tune ANL/BNL

- GENIE's Rein-Sehgal model overestimated large amounts of reanalysed single pion data from bubble chamber
- Performed simultaneous fit of M_a^{res}, RES norm., DIS norm. to all CC1π channels from ANL and BNL in E_ν and Q^2





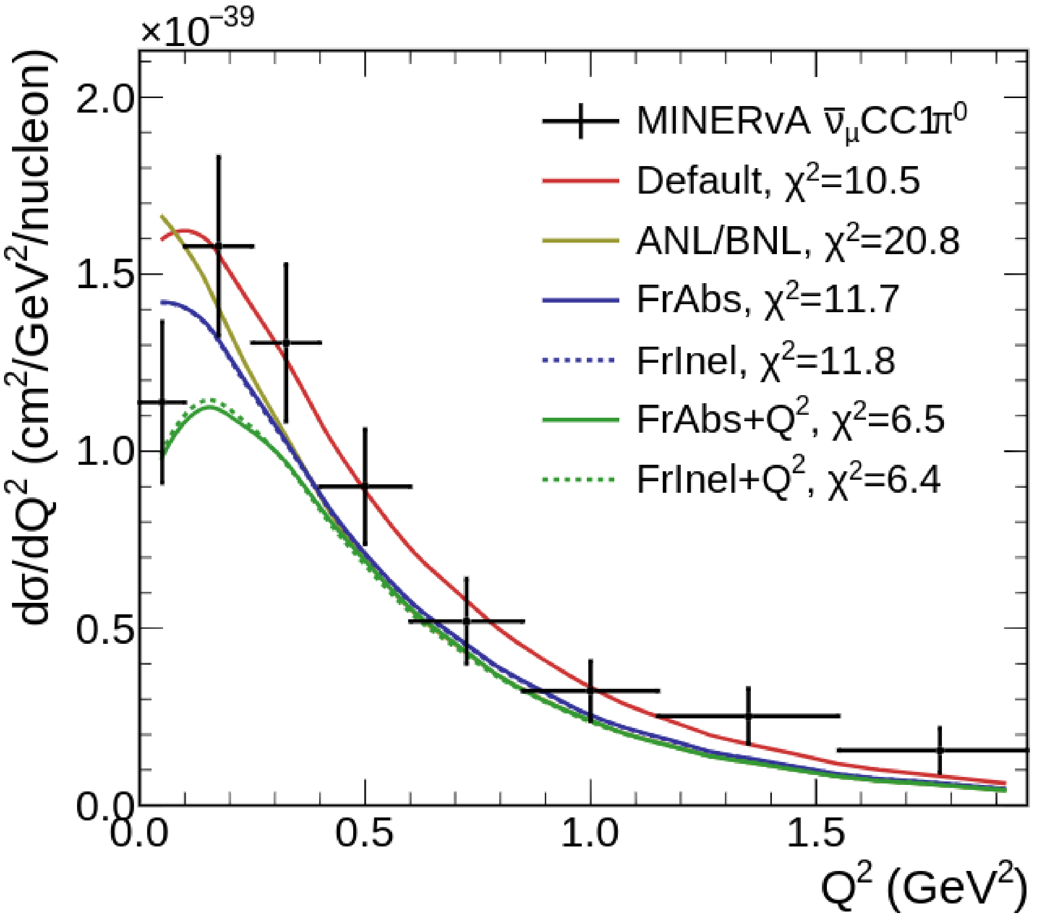
(d) BNL Q^2

- DIS norm (making up the non-res background in GENIE) pulled down to **43%** of nominal, resonant normalisation up by **15%** and M_a^{res} from **1.12→0.94 GeV**

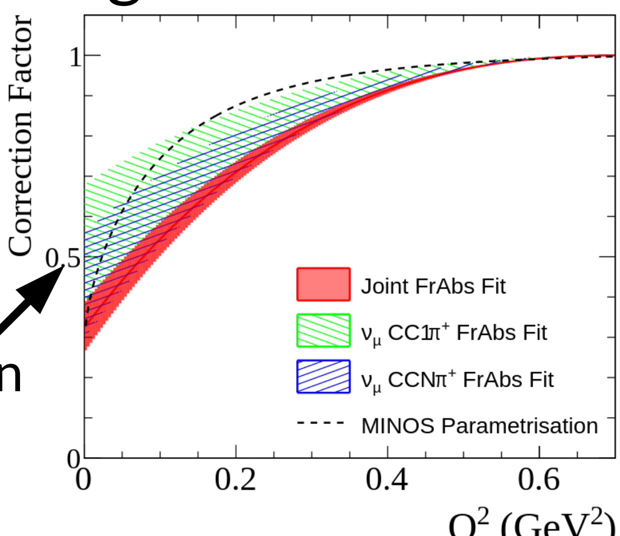
K. Eur. Phys. J. C (2016) 76

Pion tune MINERvA NUISANCE

- Worked with MINERvA to produce 1π GENIE tune
- Used published MINERvA data, simultaneously and separately fitting the different interaction channels
- Introduced a Q^2 dependent suppression, inspired by MINOS, MiniBooNE and MINERvA data
- But also found CC1π^0 and CC1/Nπ^+ preferred different tuning
- Implies unmodelled nuclear effect lurking



~50% suppression at low Q^2



Stowell et al, arxiv

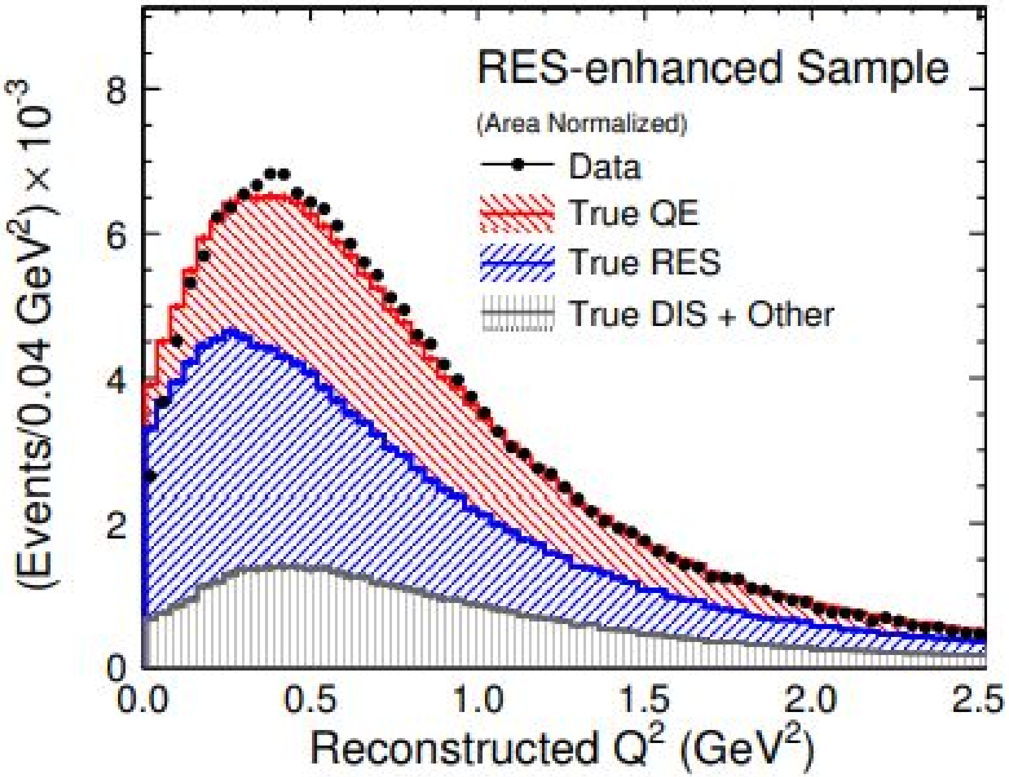
Experimenters' tunes

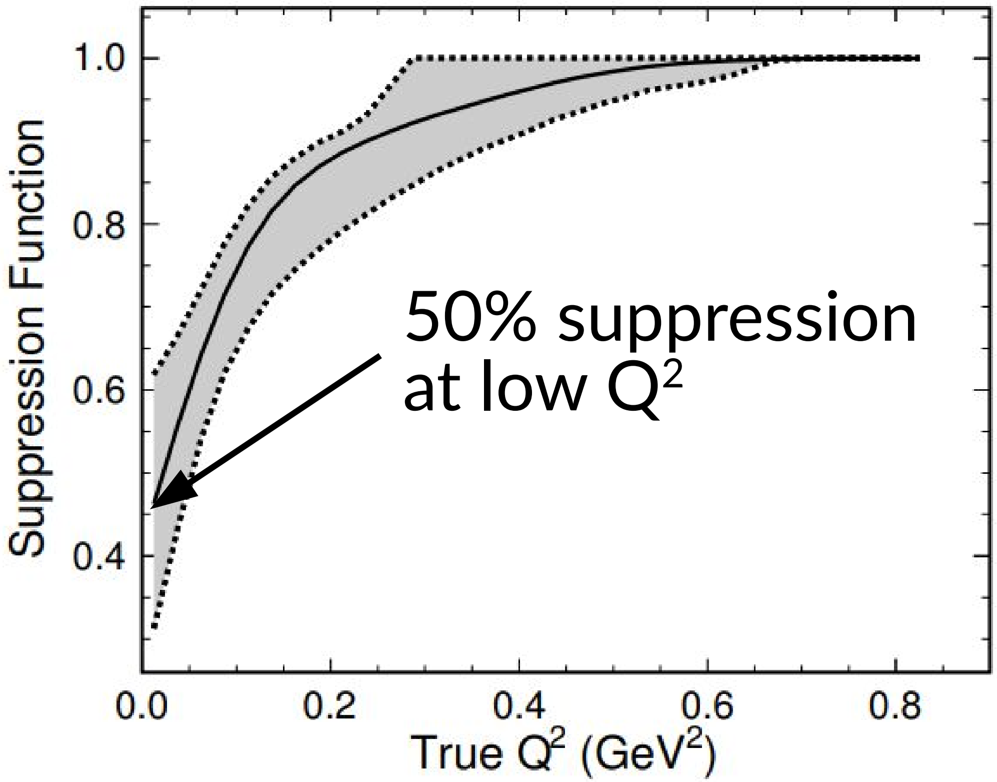
MINOS

- Oscillation analyses studied CC-inclusive
  - Included largely normalisation uncertainties
  - Pion absorption estimated by 100% and 0%
- CC-inclusive cross-section
  - Varied axial masses by ~15%
  - Went in the Bodek-Yang DIS implementation and varied parameters, compared to the original data, and built uncertainty bands
- CCQE cross-section
  - Studied side-bands and found resonant enhanced low Q^2_{rec} poorly modelled

MINOS CCQE analysis

- Inspired by their resonant-enhanced side band, MiniBooNE CCQE, CC1π0 and CC1π+ data





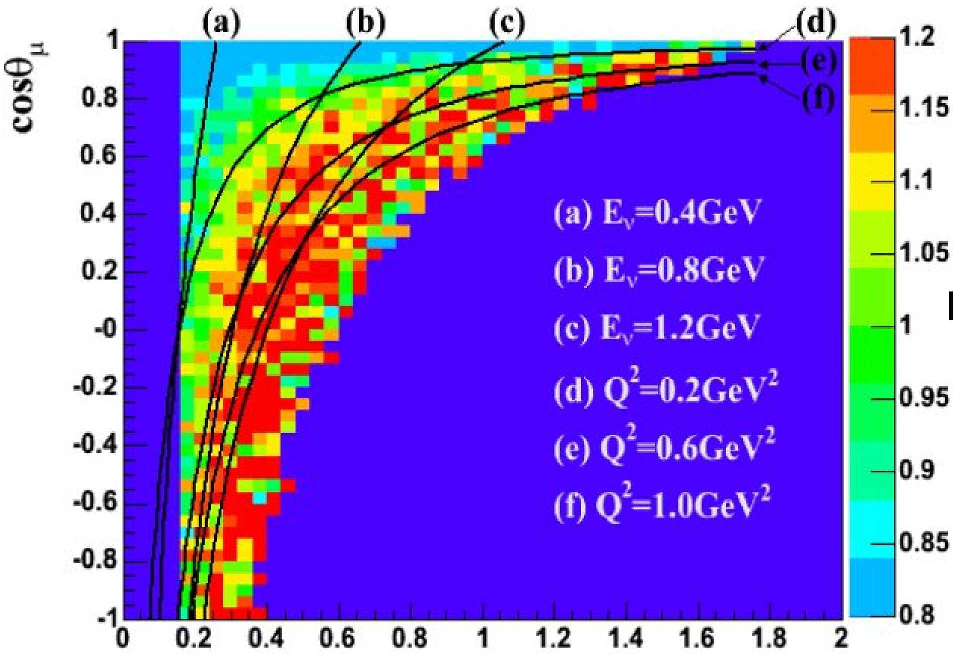
- Suppression at work until Q^2=0.7 GeV^2

$$R = \frac{A}{1 + \exp\{1 - \sqrt{Q^2}/Q_0\}}$$

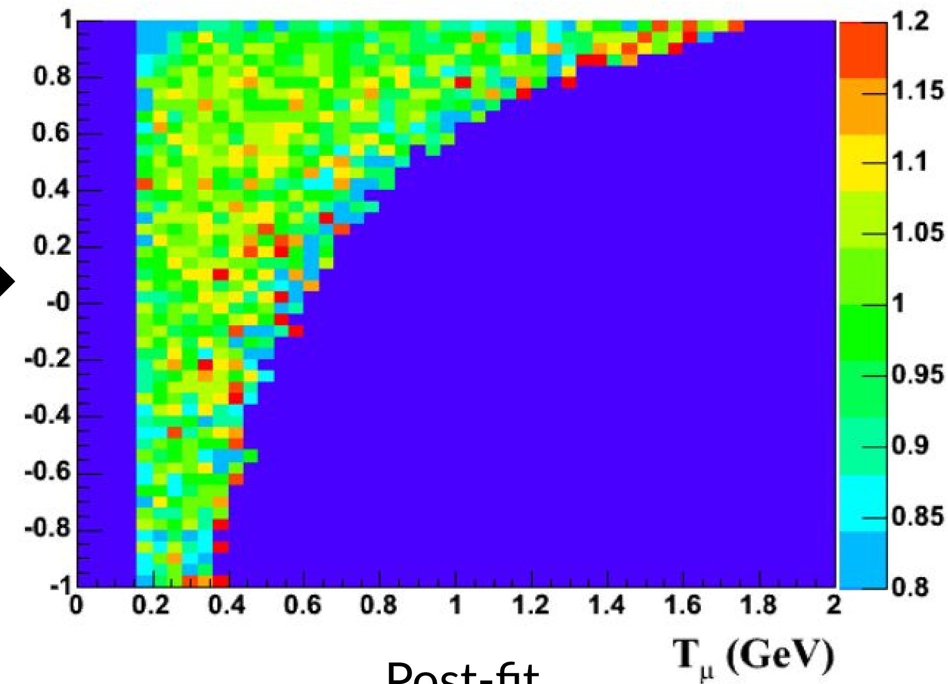
A=1.010
Q_0=0.156 GeV

MiniBooNE

- MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation search modified interaction model from their CCQE and NC1π^0 measurements



Pre-fit NUANCE prediction



Post-fit

- Tuned M_A^{QE} and Pauli blocking parameters to CCQE data
- Used alternate models for ν_μ/ν_e scaling
- Added E_ν dependent error to account for higher E_ν
- CCQE normalisation and ν/anti-ν normalisation

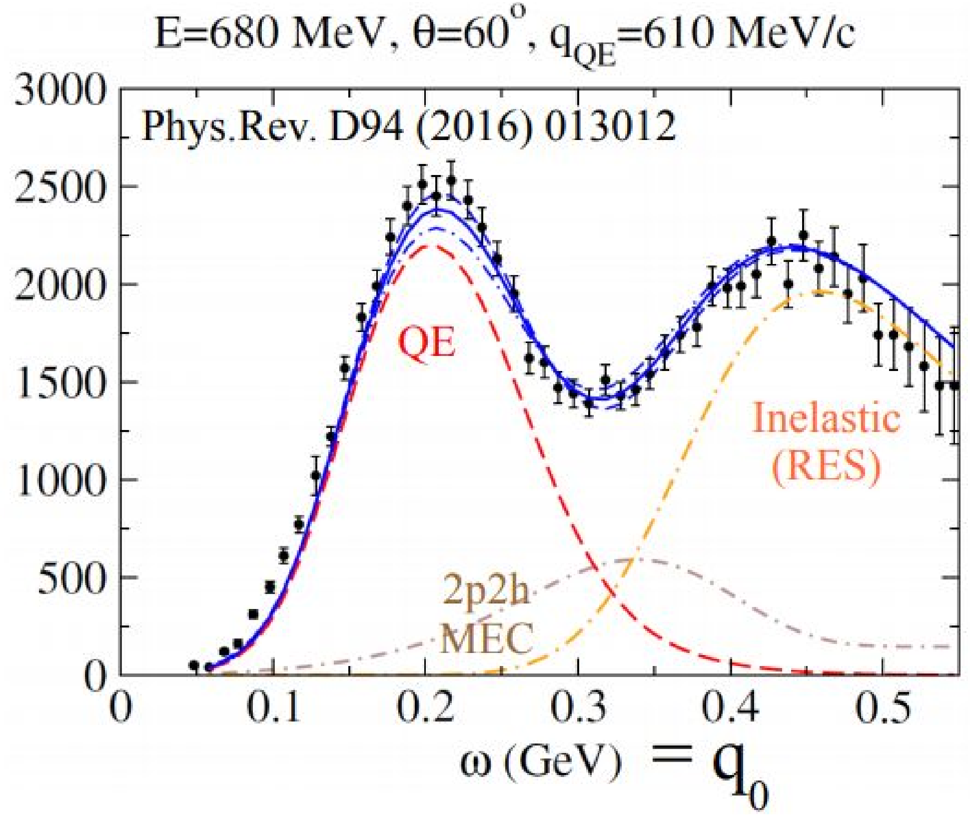
T. Katori, NuInt14

MiniBooNE

- Propagated the uncertainties through "multi-sim" method, commonplace today
  - Vary systematics one at a time by 1σ, build prediction with new variation, repeat, construct total covariance
  - Does not account for correlations between systematics
- Simulation did not include 2p2h → "inflated M_A^{QE} puzzle"

MINERvA base tune

- Uses GENIE with Nieves 2p2h, applying RikRPA and the ANL/BNL non-resonant tune
- Inspired by electron scattering highlighting the 2p2h region in q_0, studied CC-inclusive events in E_{av} and q_3

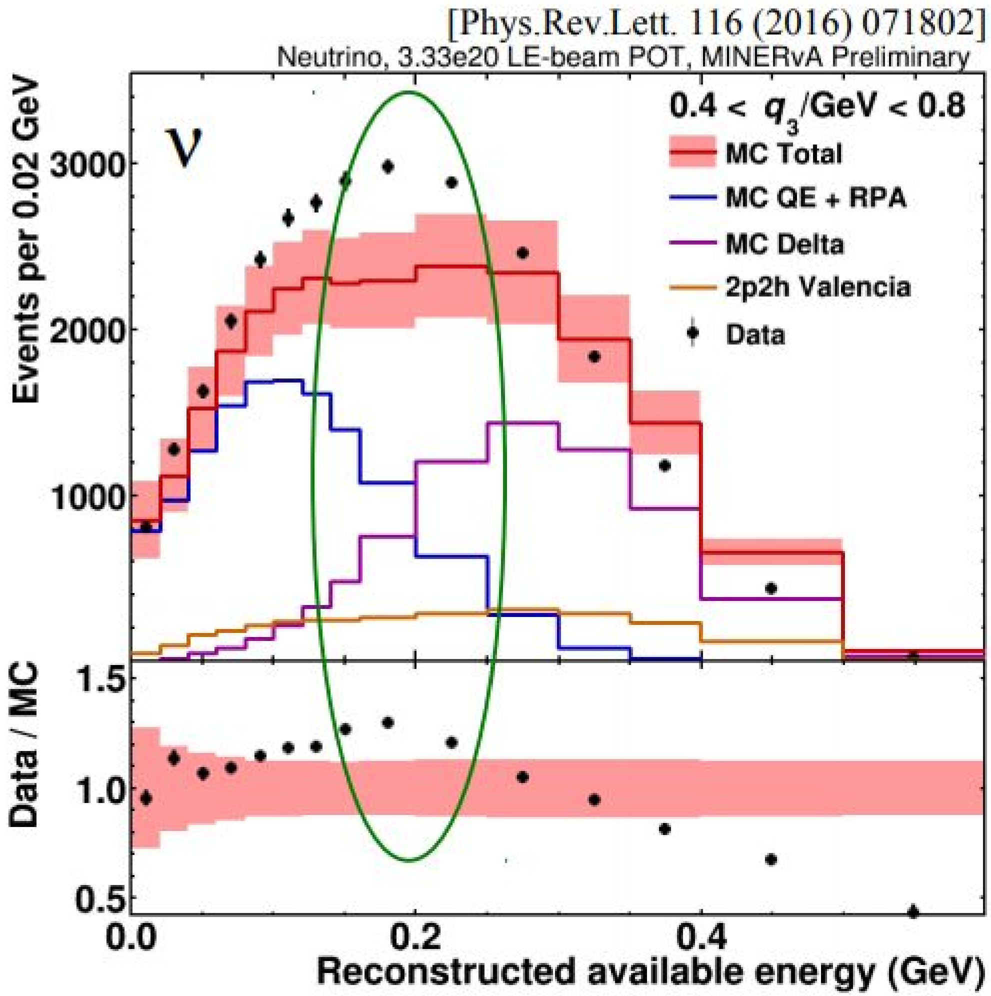


$$E_{\mathrm{av}} = \sum T_p + \sum T_{\pi^\pm} \quad \text{No neutron included}$$
$$+ \sum E_{K^\pm} + \sum E_{e^\pm} + \sum E_{\pi^0} + \sum E_\gamma$$

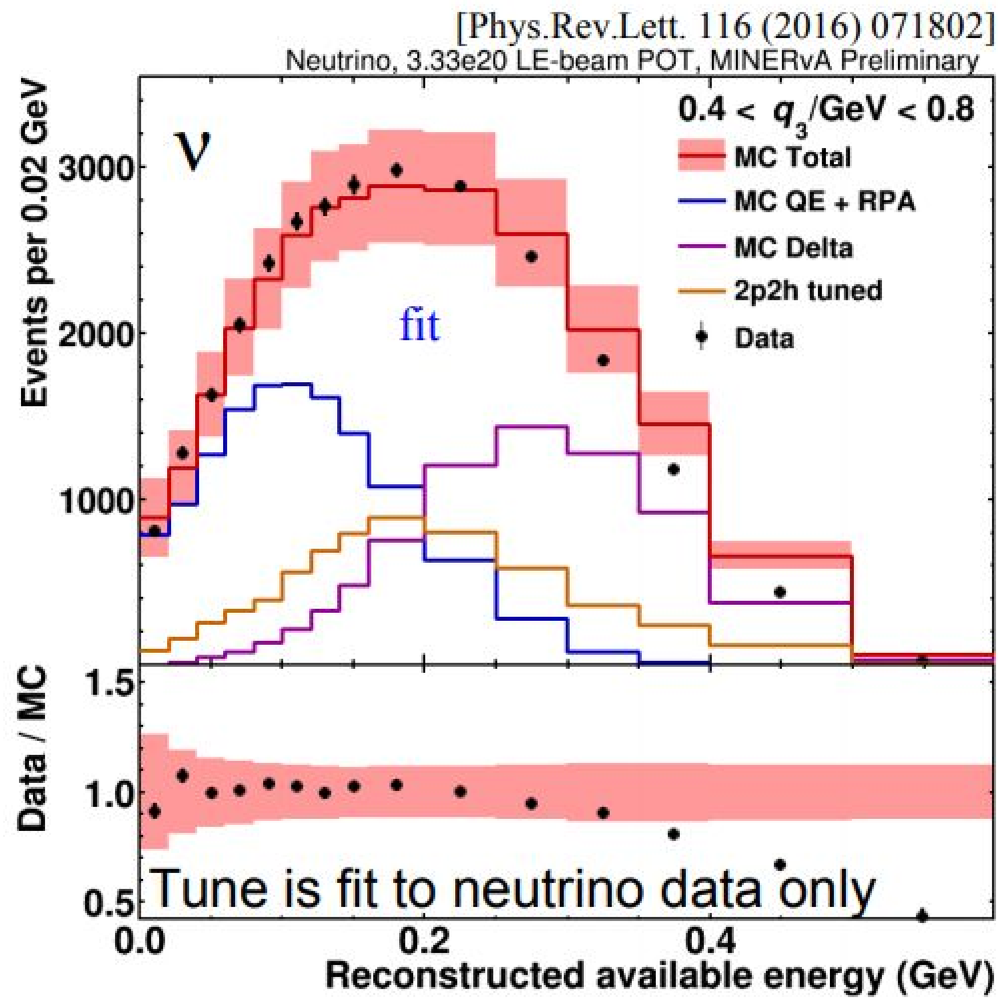
MINERvA 1pi tune R. Gran, NuInt17 X-G Lu, NuInt18

MINERvA 2p2h

- Cross-section in crucial region too small, even with Nieves 2p2h
- Fit Gaussian blob to true 2p2h events in q_0, q_3 → MnvTune!



GENIE+pion+RPA+Nieves 2p2h

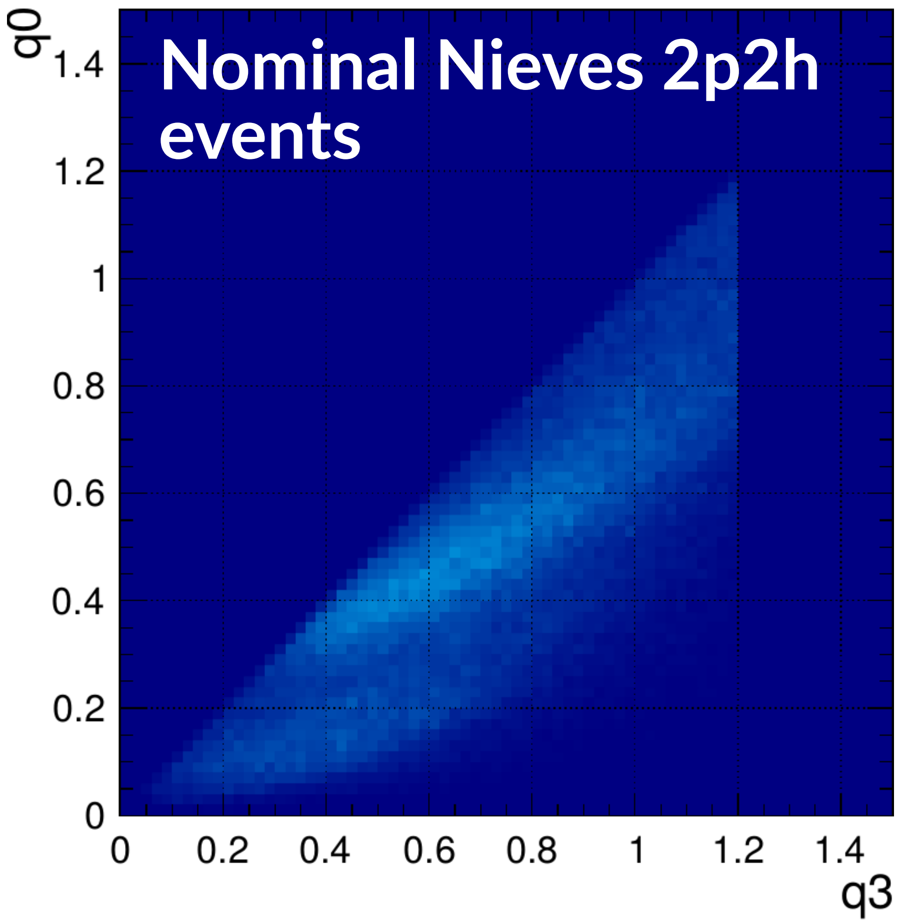


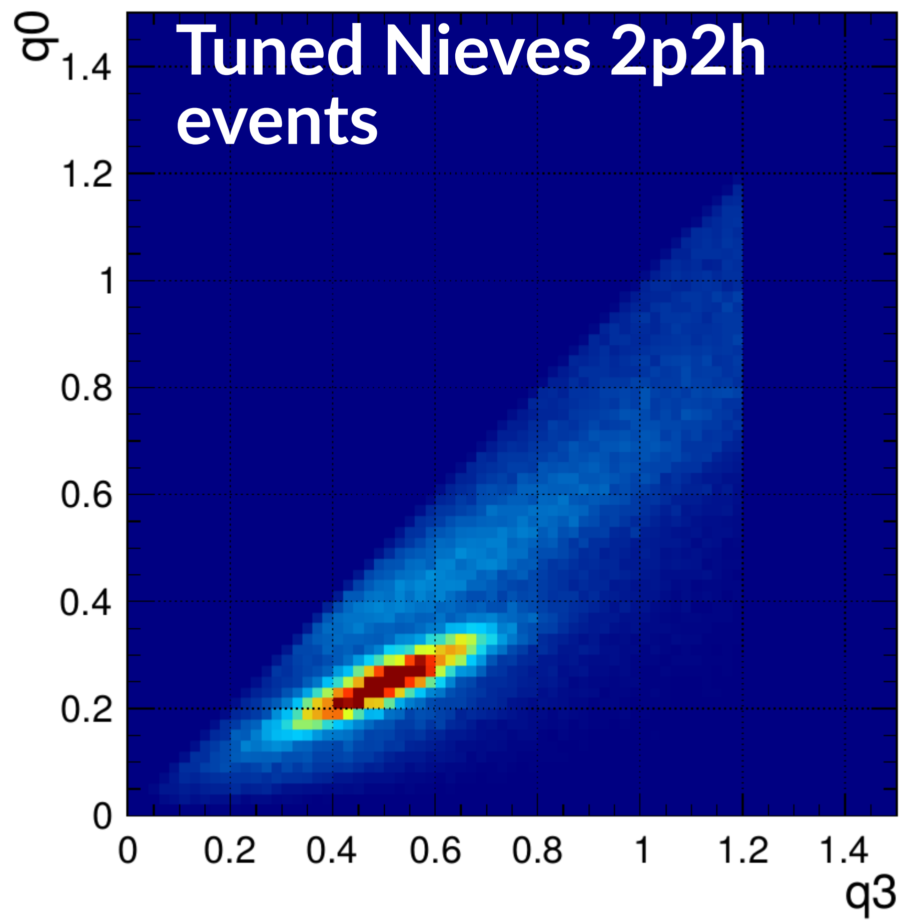
GENIE+pion+RPA+Nieves 2p2h+blob

MINERvA 1pi tune R. Gran, NuInt17 X-G Lu, NuInt18

MINERvA 2p2h

- Enhances 2p2h cross-section considerably



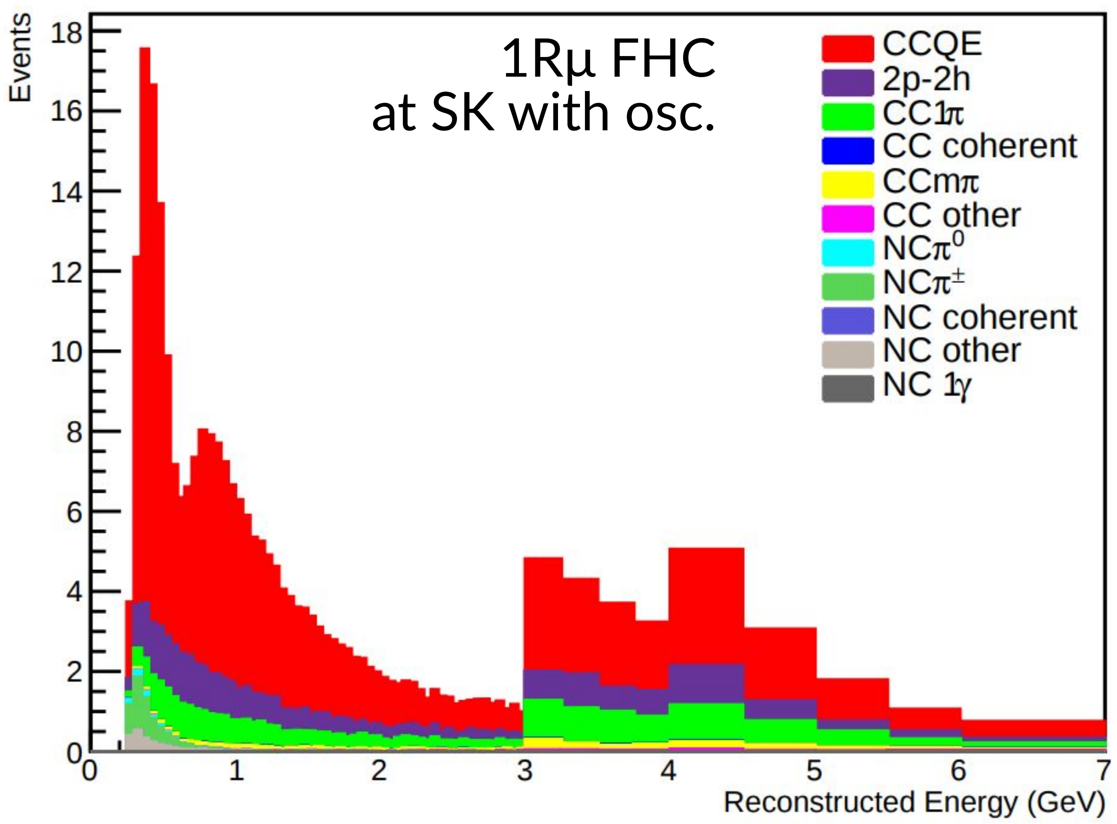


- Can also distribute the new cross-section to purely 2p2h np, purely 2p2h nn, and purely CCQE
- Exploring alternative DIS models for future publications

MINERvA 1pi tune R. Gran, NuInt17 X-G Lu, NuInt18

T2K

- NEUT is the base generator for T2K and SK
  - Similar suite of default systematics to GENIE
- Oscillation analysis targets CC0π, so systematics focuses on CCQE, 2p2h, pion+FSI, and initial state effects

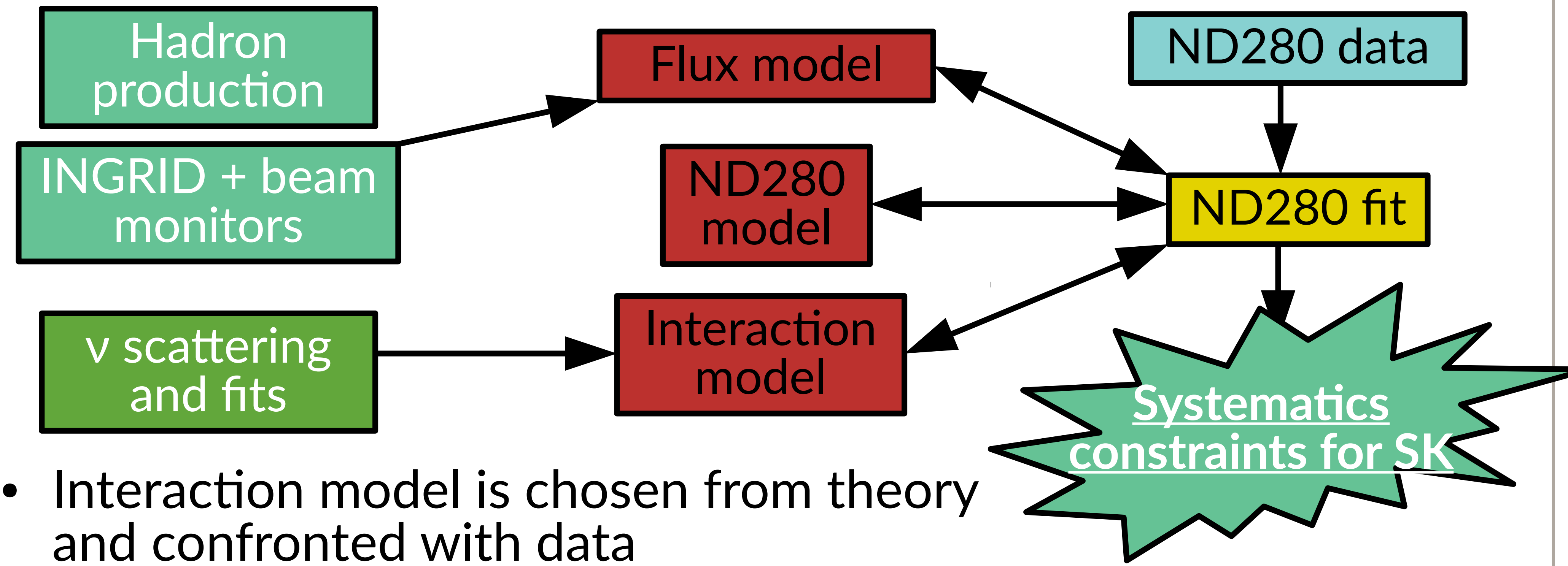


- Also concerned by ν/anti-ν modelling, and $^{12}C \rightarrow {}^{16}O$

Me, NuFact 2018

T2K

- Use a near-detector to constrain the model, fitting flux, cross-section and detector model with reasonable priors
- Pre-fit uncertainty on CC-inclusive selection is 11%, post-fit about 2%

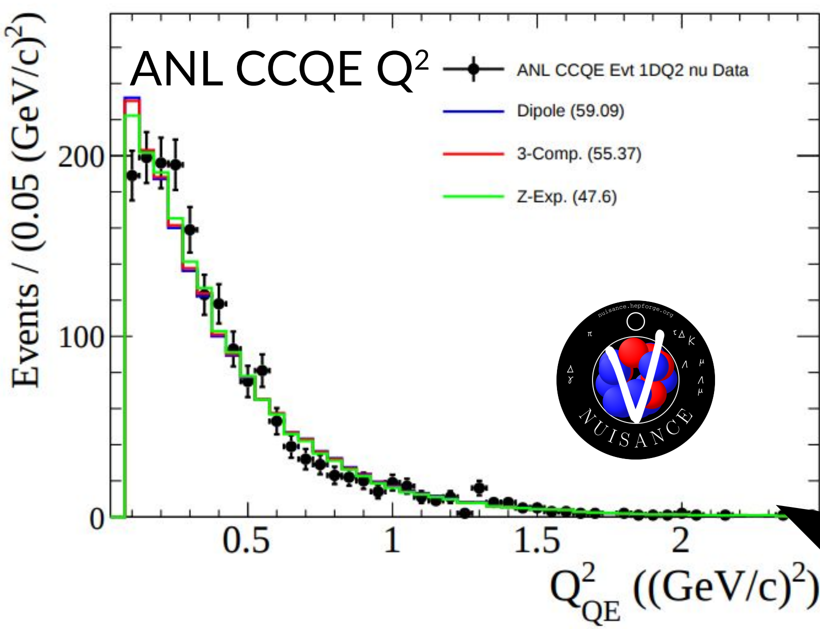


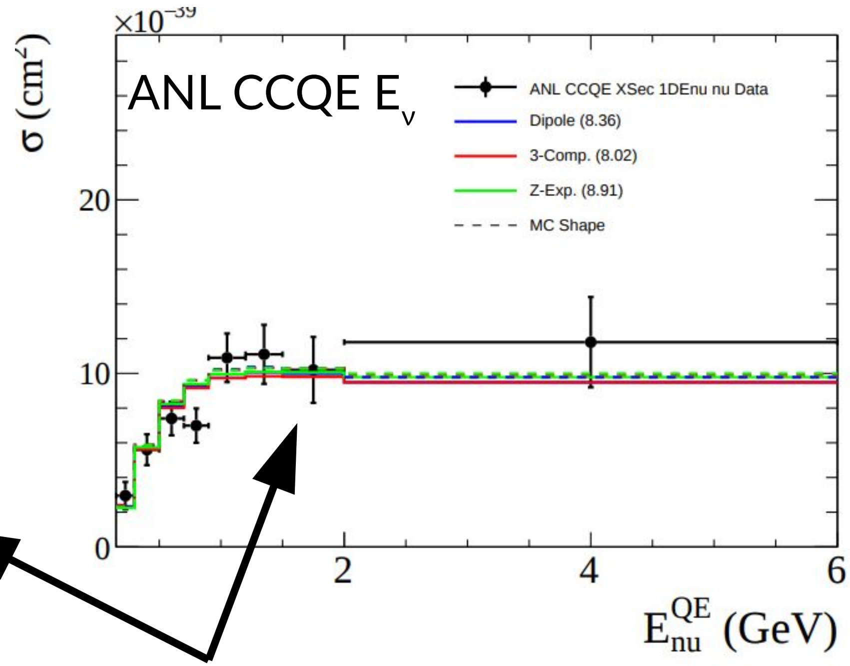
- Interaction model is chosen from theory and confronted with data
- Different approach to MINERvA and NOvA: large simultaneous fit

Me, NuFact 2018

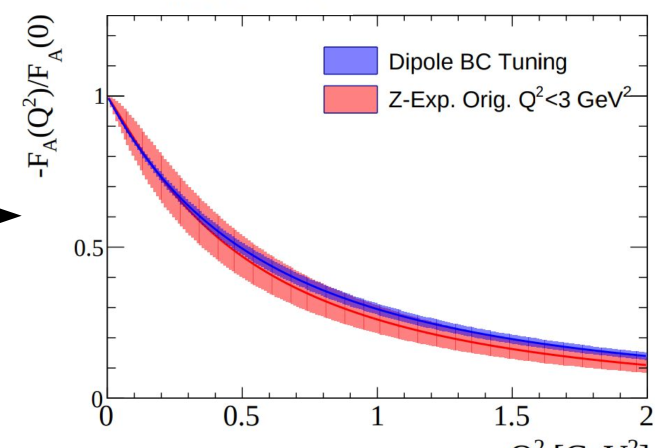
T2K constraints, CC0π

- M_A^{QE} is initially set to 1.2 GeV/c², but unconstrained in ND280 fit
  - Fitting to corrected ANL, BNL, FNAL data, M_A^{QE} = 1.08 ± 0.04 GeV
  - Also fit alternative form-factors, z-expansion and three component





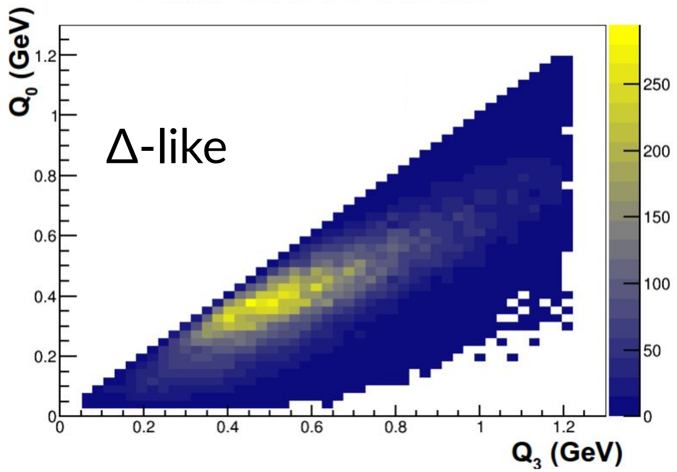
- Z-expansion and three-component better fit than dipole
- Error band for z-expansion is ~constant with Q²: not the case for dipole
  - High Q² not dictated by low Q²

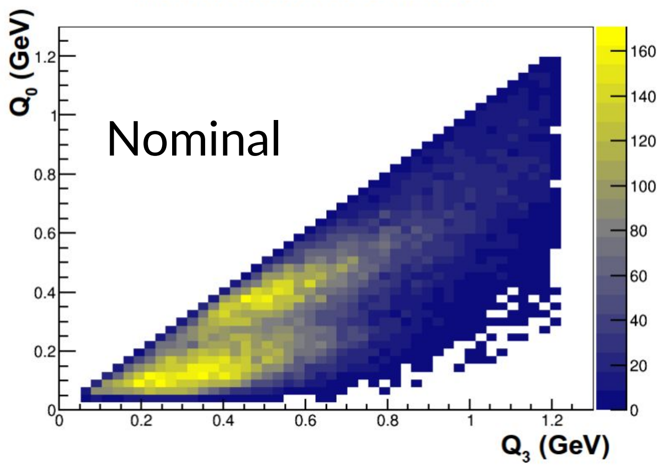


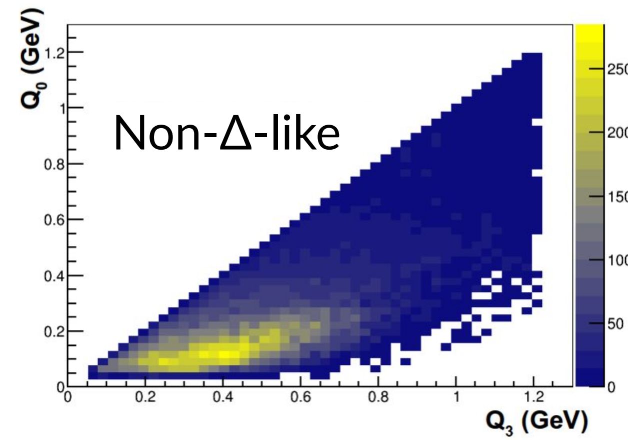
P. Stowell NuTune2016 Me, NuFact 2018

T2K constraints, 2p2h

- 2p2h shape parameter puts the 2p2h as Delta-like or non-Delta like in Nieves model
  - Separated for Carbon and Oxygen and correlated 30%

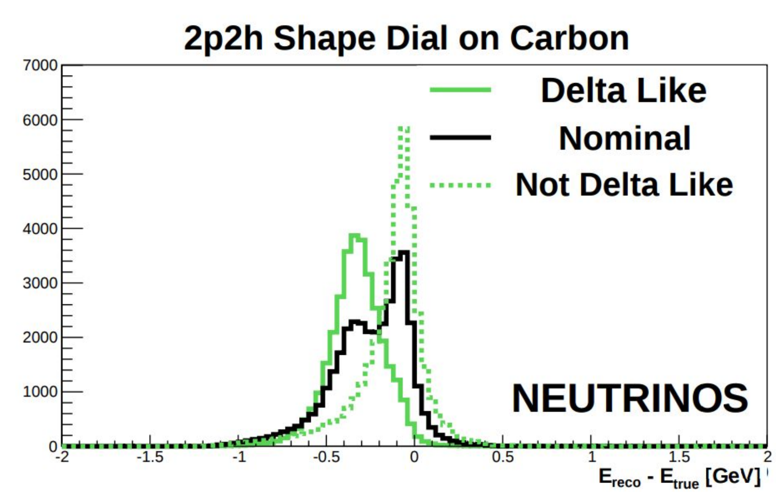






- 2p2h normalisation parameters for ν and anti-ν

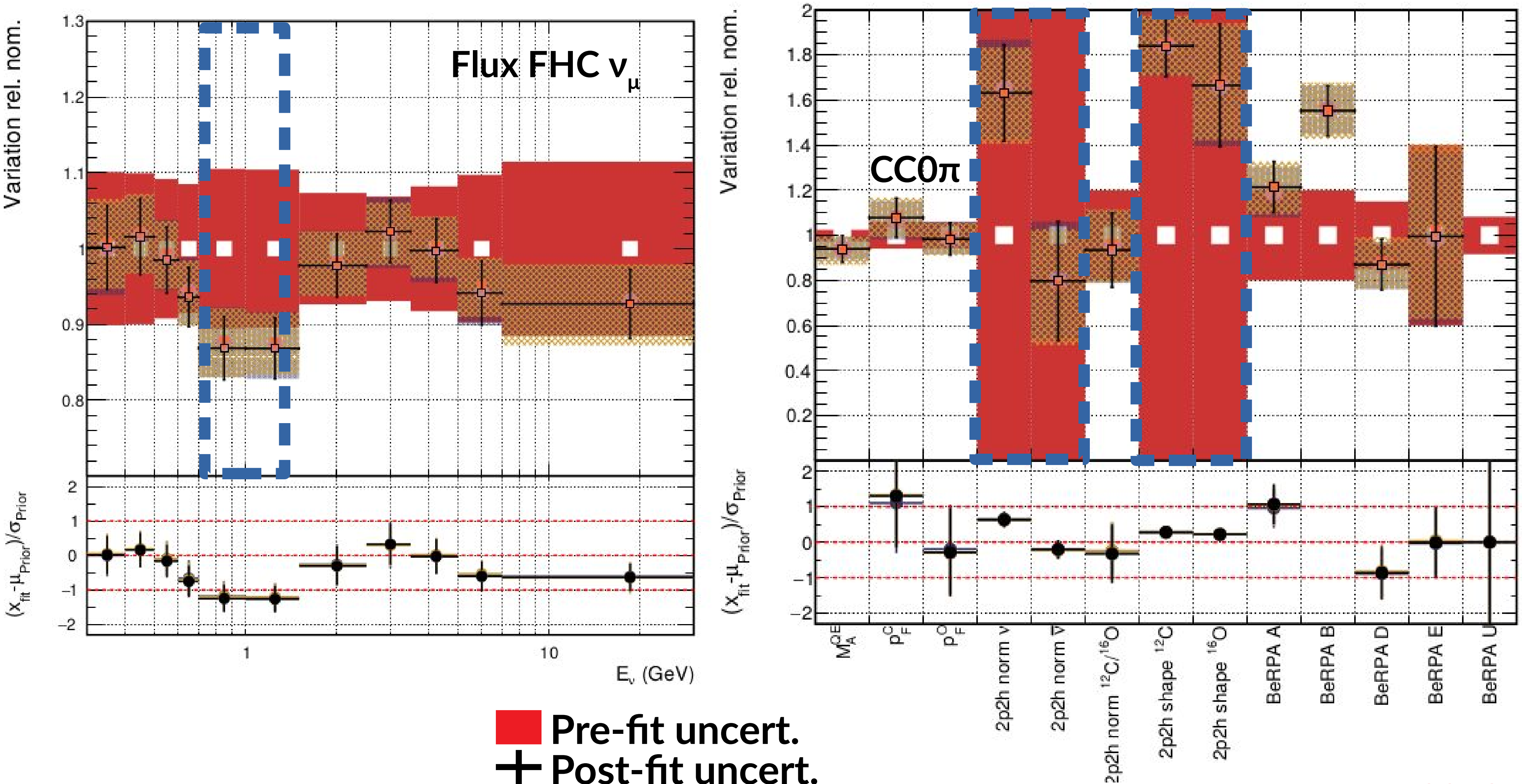
  - Constrained 2p2h C→O extrapolation normalisation parameter: 30% uncertainty
  - No constraints from external data



Me, NuFact 2018

The T2K near detector fit

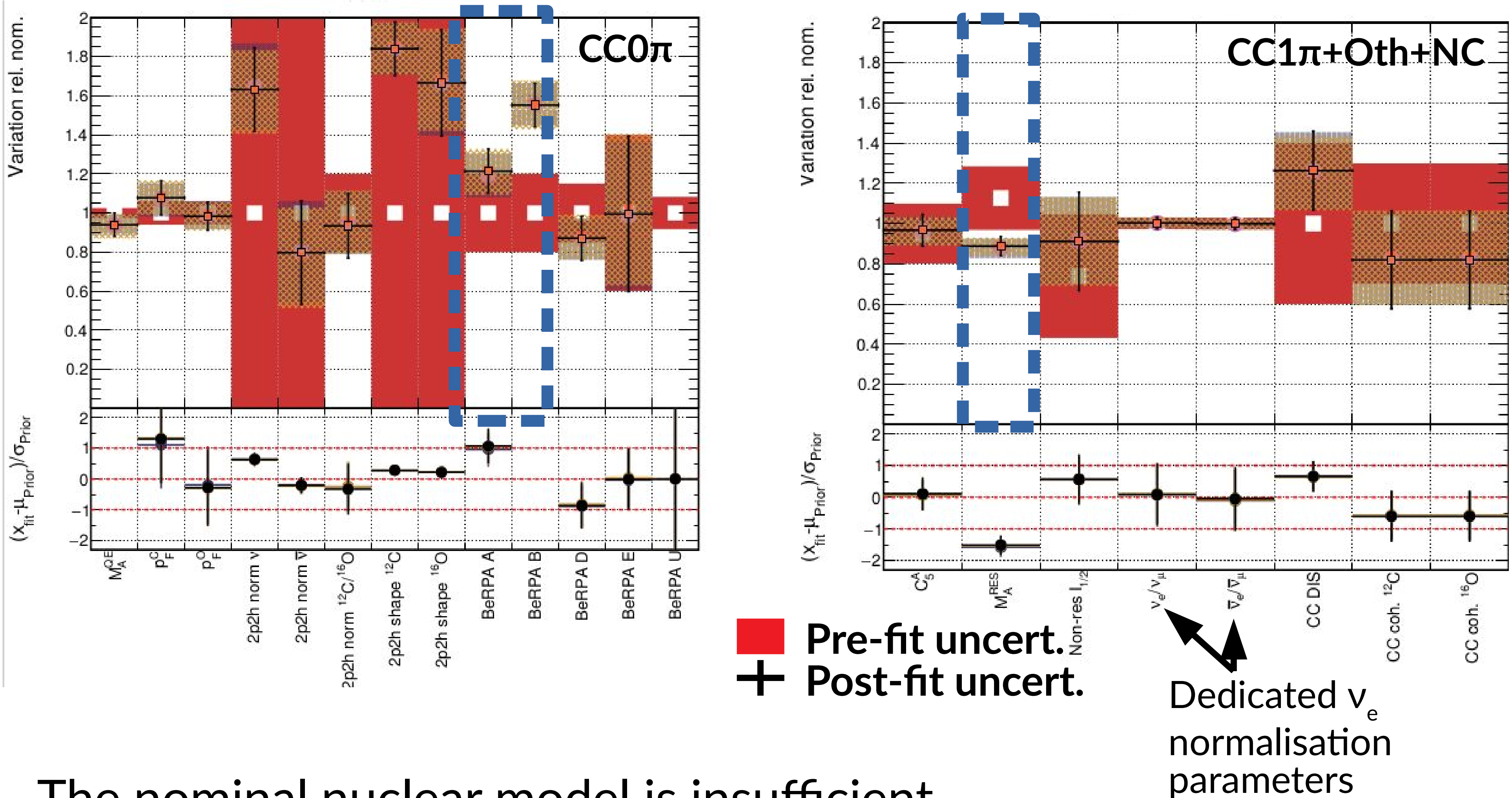
- ~1 GeV flux pulled to 0.9
- 2p2h shape parameters pushed to boundary
- 2p2h normalisation different for ν and anti-ν



Me, NuFact 2018

The T2K near detector fit

- RPA parameters pulled outside priors, much lower M_A^{RES}



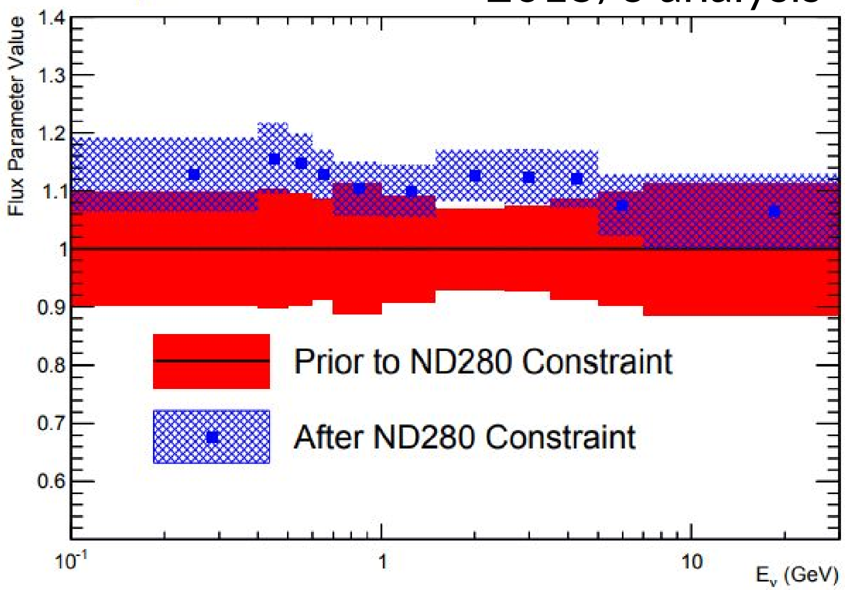
- The nominal nuclear model is insufficient
  - An effective T2K-only model in the making? Seems likely
  - Evaluate by extensive comparisons/fits to external data

Me, NuFact 2018

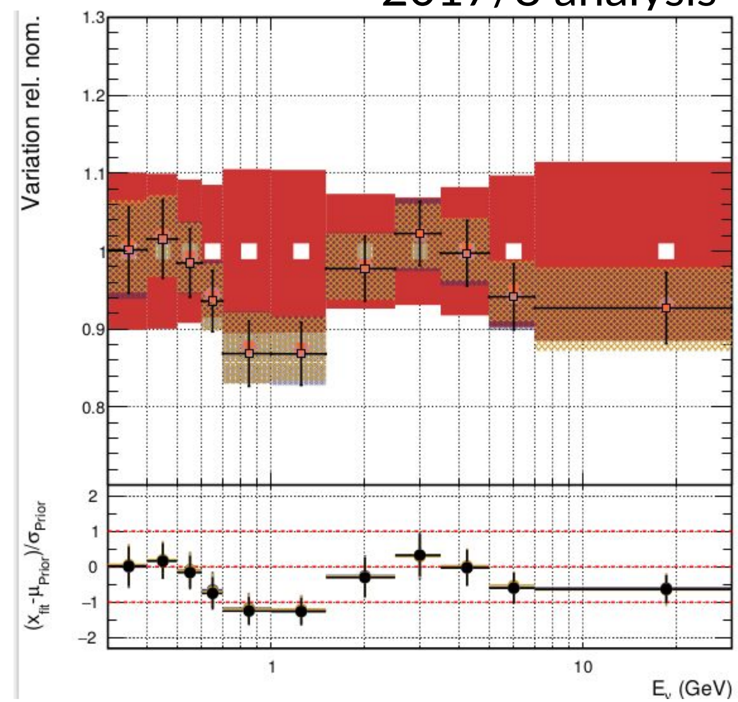
The T2K near detector fit

- The 2015 flux increase is now absorbed in the RPA parameters

2015/6 analysis



2017/8 analysis



- Replacing one bad egg with another?
- ND280 data wants a Q^2 (q_0, q_3?) dependent correction
- Evaluate the post-fit interaction model against neutrino scattering data to gauge how T2K-specific the tune is
  - Also test MINERvA model against our data for comparison
- Are rethinking some of this with our new production for 2019

Me, NuFact 2018

Mock data studies

- Evaluates impact of interaction model choice on extracted oscillation parameters
- Reweight simulation to some model not covered in the simulation, and set these template to be the "mock data"
- Fit the simulation at ND280 and SK with the normal model to the "mock data"
- Check to see if the extracted oscillation parameters differ to when using the normal model as data ("Asimov")
- If large difference, devise method for oscillation parameter inflation

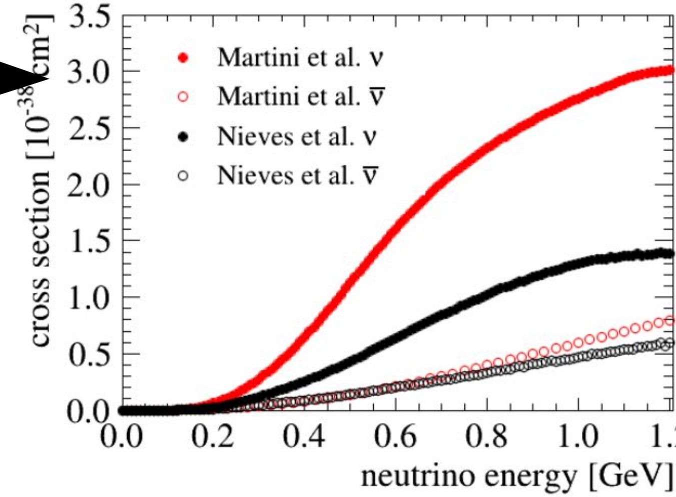
- Is not equivalent to re-running simulation, but approximate and much less time-consuming

- N.B. this happened for the binding energy parameter, E_B, and Δm^2_{23}, in last year's analysis

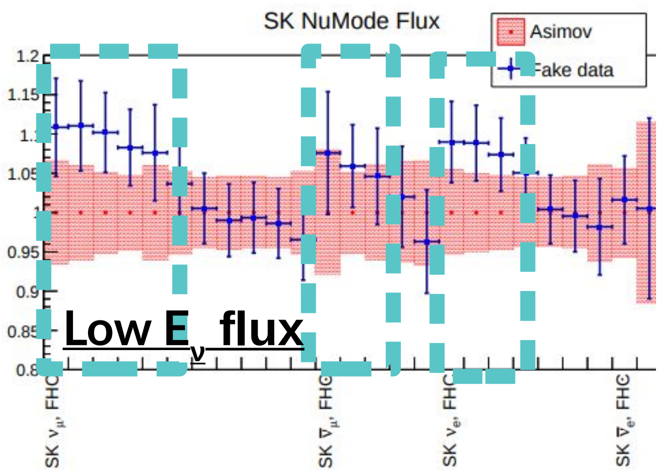
Me, NuFact 2018

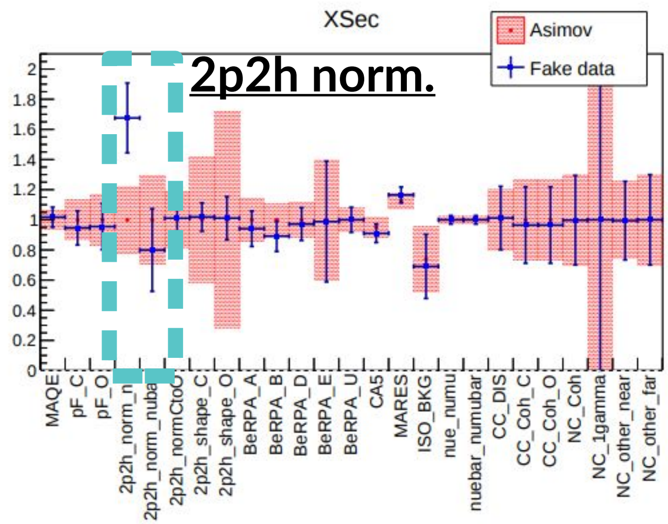
Example of mock data

- 2p2h prediction from Martini vs Nieves

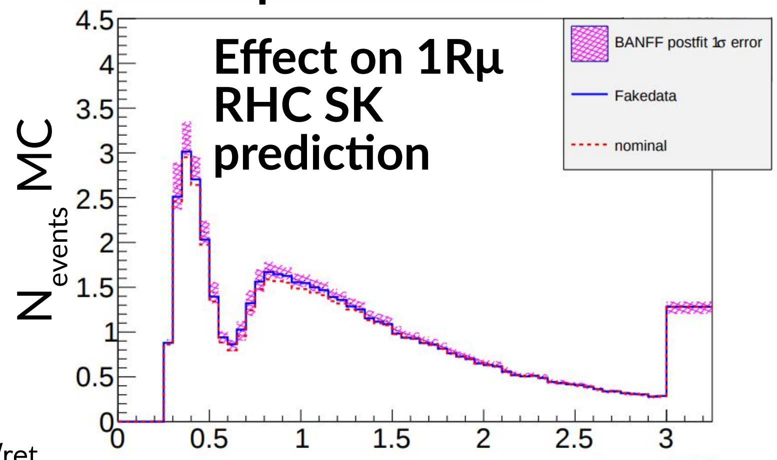


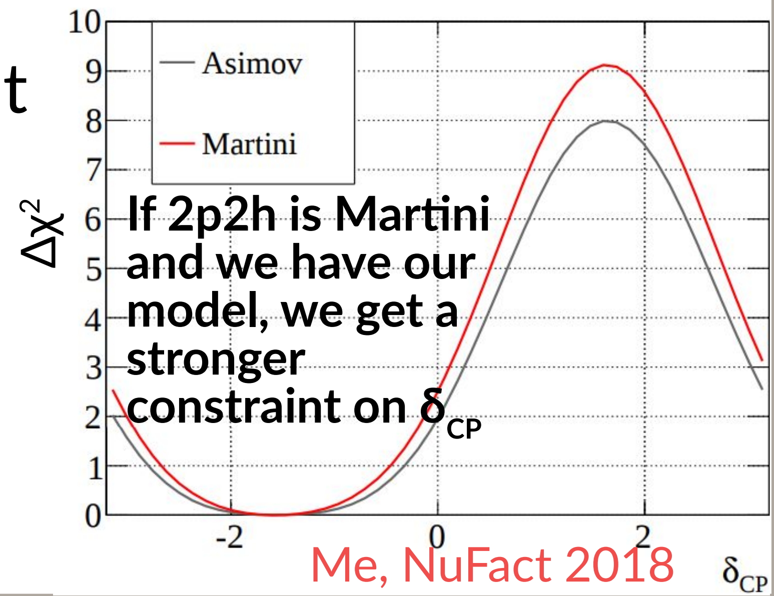
- Near detector fit shows change in flux and 2p2h norm for ν





- Make SK prediction from ND280 and fit





Me, NuFact 2018

NOvA base model

- Starts with a model similar to MINERvA, GENIE 2.12.xx

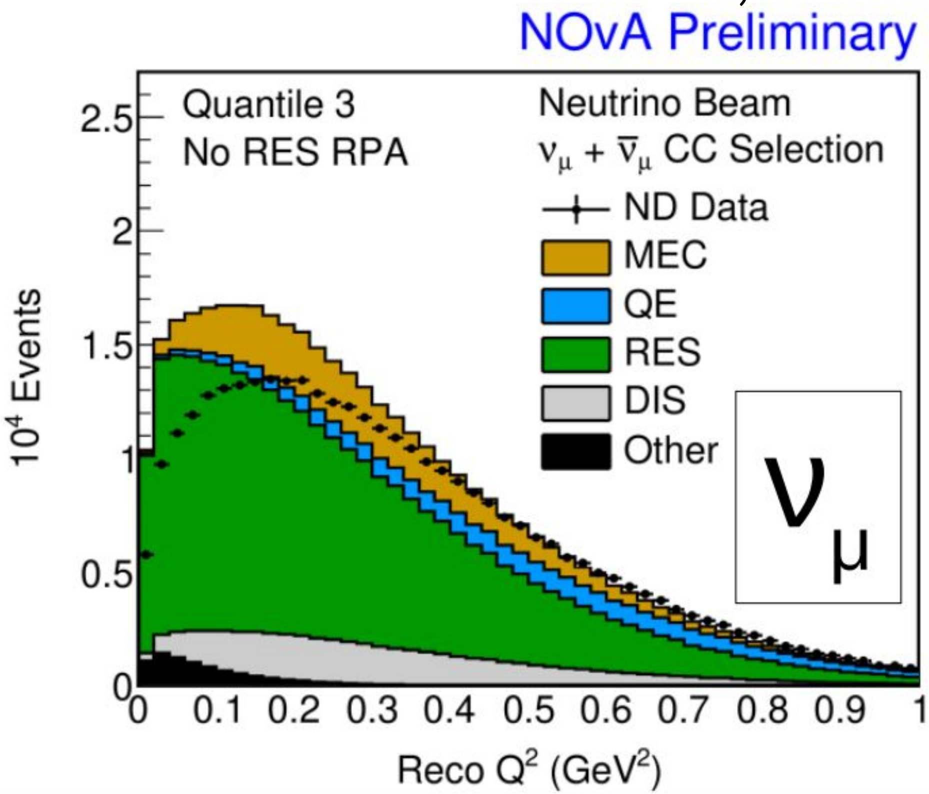
"How can we provide robust oscillation results in the intermediate time before a real comprehensive model is available in general-purpose tools?"

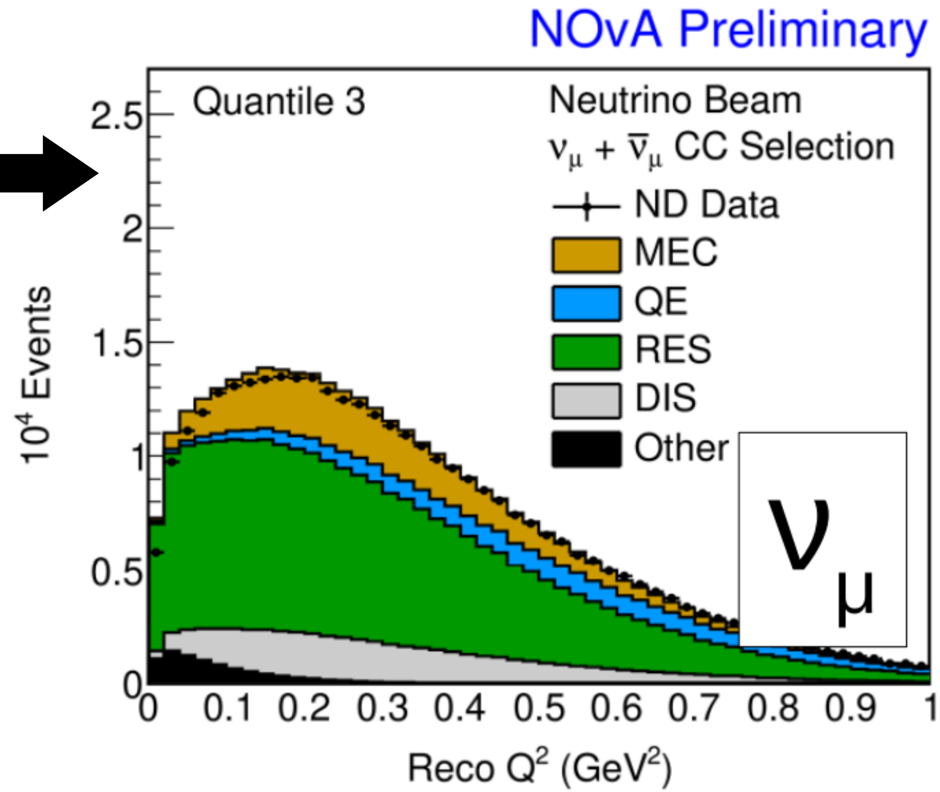
- Replaces Nieves 2p2h with Empirical MEC (Dytman) because it has an NC calculation
- As MINERvA, applies RikRPA and single pion bubble chamber tune
- Additionally tunes M_A^{QE}=1.04 from recent analysis

J. Wolcott, Tensions 2019 J. Wolcott, PINS 2019

NOvA 1π suppression

- NOvA's resonant-enhanced samples seem to want a low Q^2 suppression
  - Much akin to MINOS, MiniBooNE and MINERvA





- Suppressing true resonant events by same method as RikRPA seems to steer things in promising direction
- Use same uncertainty, but uncorrelated with CCQE

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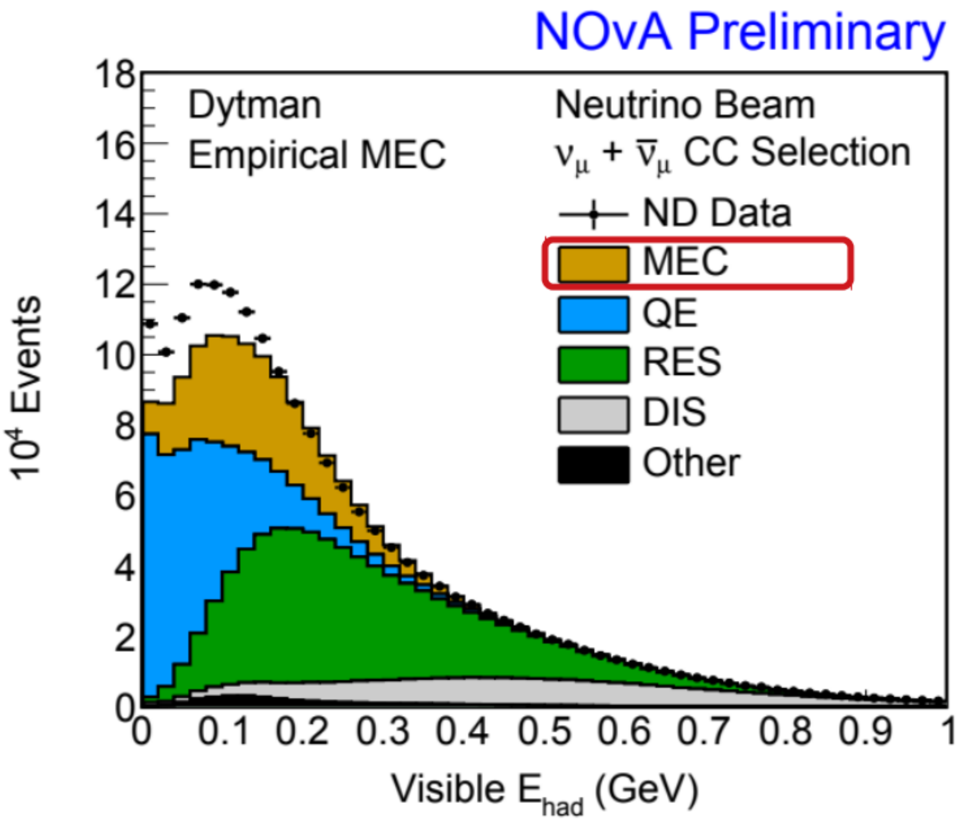
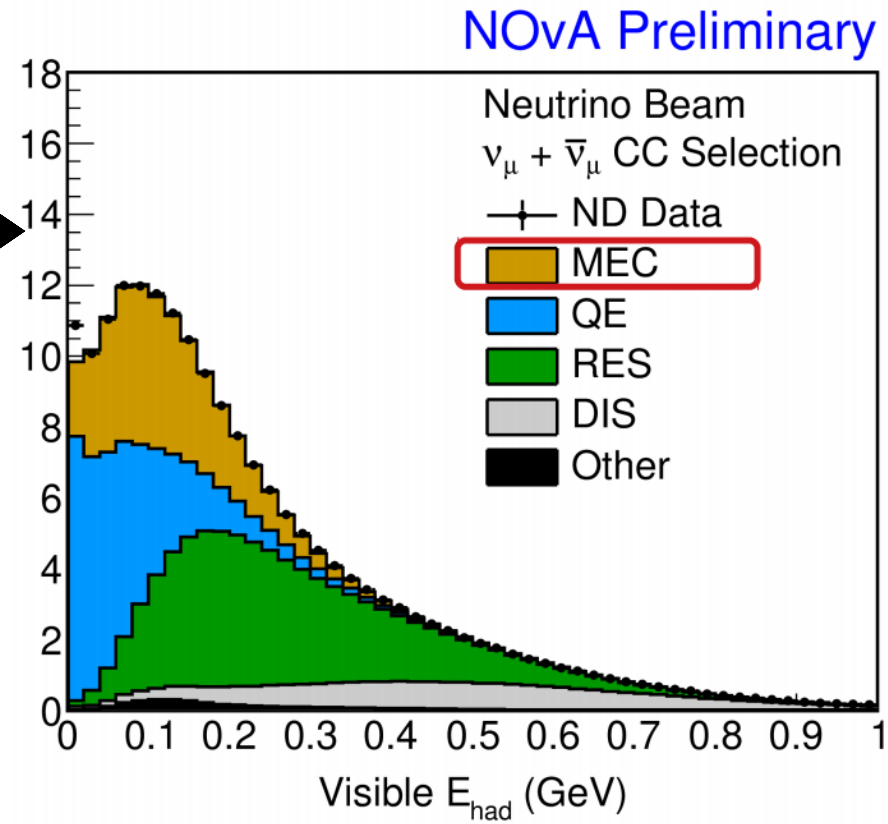
NOvA 2p2h tuning

- The final ingredient tunes the Empirical MEC model to NOvA's CC-inclusive selection, weighting in q_0, q_3





- Reproduces the ND spectra very well by design
  - Enhances 2p2h cross-section considerably

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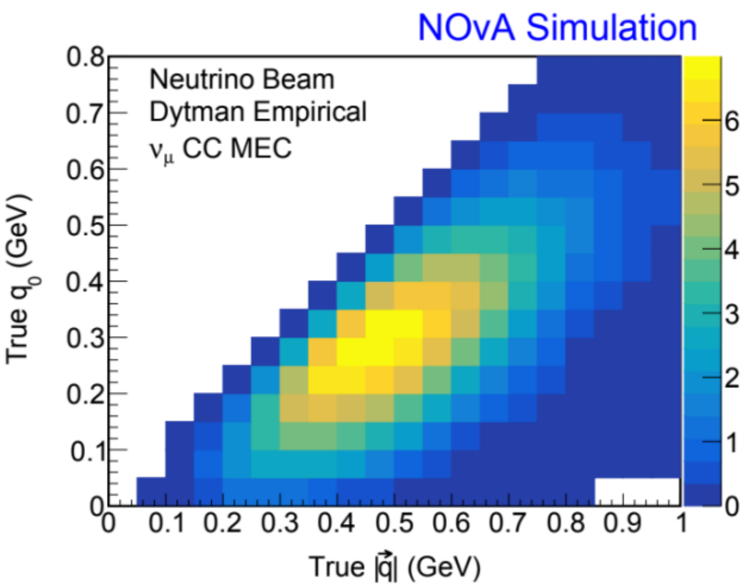
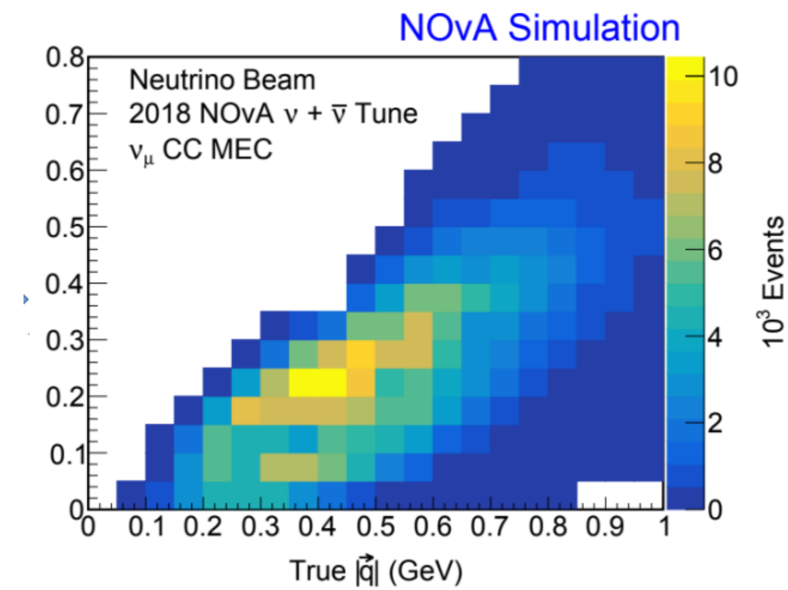
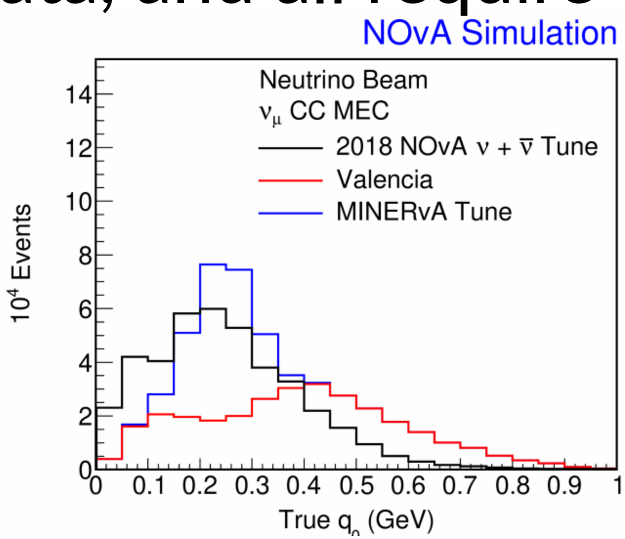
NOvA 2p2h tuning

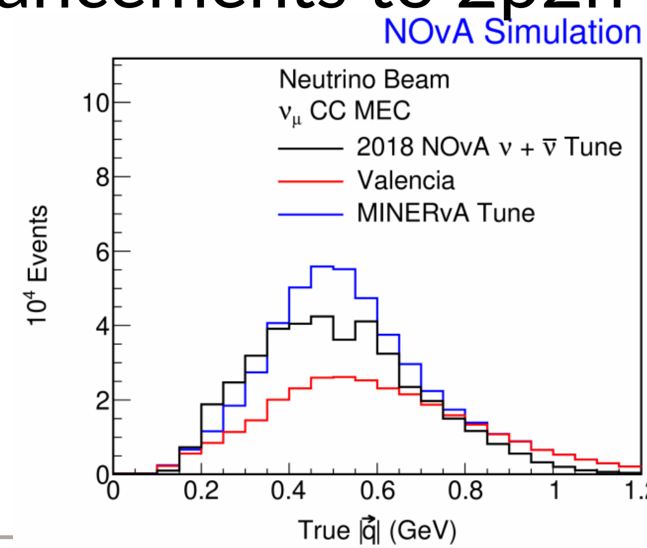
- Looking closer at NOvA's 2p2h after the ND-fit





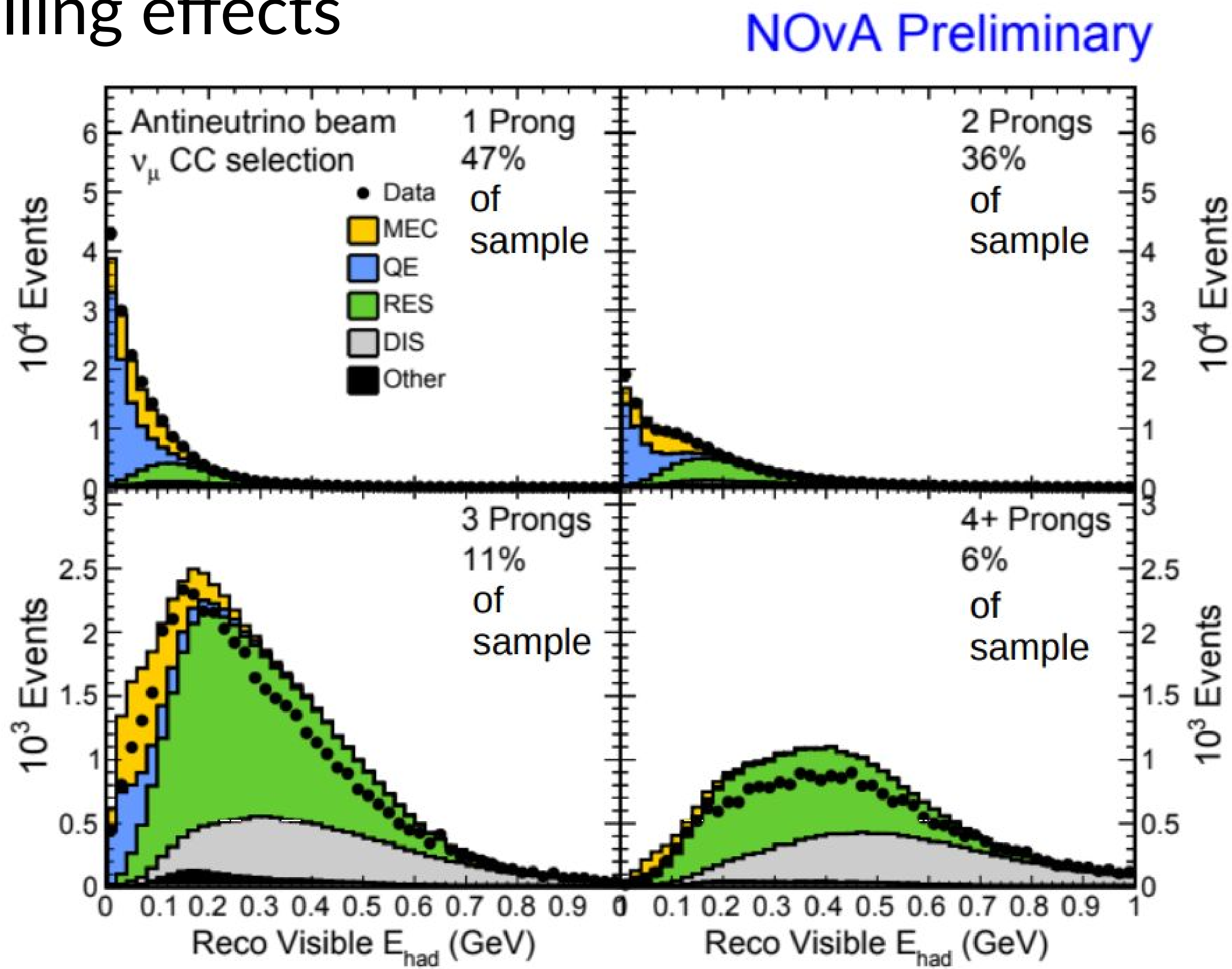
- NOvA, MINERvA and T2K start with different models, fit to their data, and all require enhancements to 2p2h





NOvA in the future

- Want to explore topological selections to enhance sensitivity to modelling effects



- And there's now GENIE v3!

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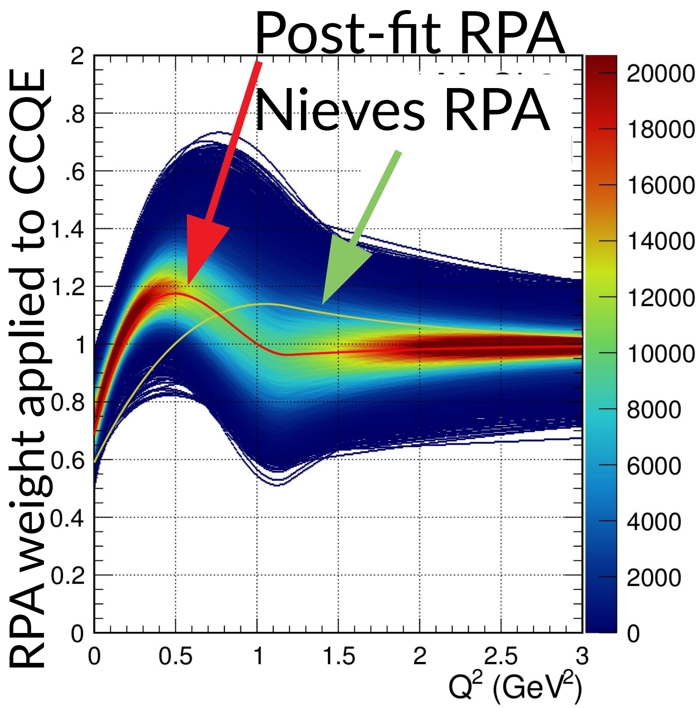
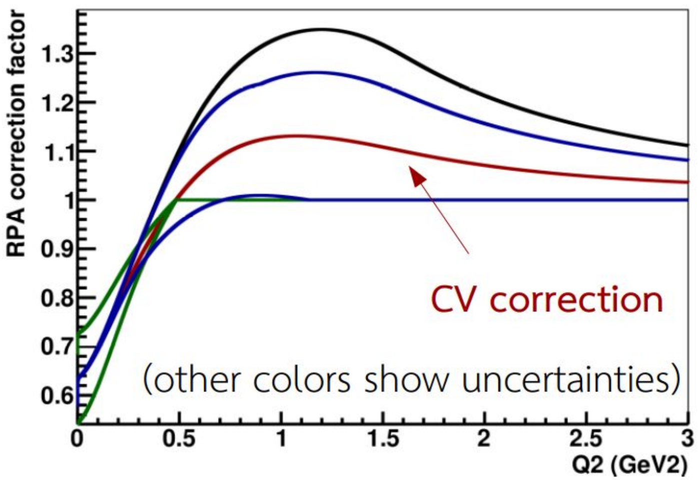
What I've heard from theorists

"You can forget about T2K RPA after the ND280 fit being any form of theory RPA"



"Applying CCQE RPA to resonant events, not the best idea ever, it's entirely different physics "



"You need to stop what you're doing and build good theory and generators before building experiments"

What I've heard from theorists

My view: we're taking more uncertain physics into account, whereas before we did not

Things I worry about

- Lack of multi-generator support on experiments
  - Efficiency corrections, selection cuts, may depend on this
- Accounting of systematics
  - Bad habit of varying GENIE/NEUT 1σ parameters
- Model dependent results affecting generator tuning

Result A
model dependent
on generator A

Generator B
Awesome model!

Tune Generator B
to Result A, get
Generator B ~
Generator A

Good theory tuned to
bad data → bad theory

- On occasion, we speak a different language to our theory colleagues
  - e.g. χ^2, fallacies of unfolding, why $\sigma(E_\nu^{True})$ is bad news

What's next?

- Moving toward more involved systematics, not necessarily reweightable ones
  - Realistic nuclear effects often mean computationally intensive, will need work
- We're building a large global data set on nuclear targets, notably C(H), with ^{40}Ar coming
- Revisit light target data, some would even argue build a new bubble chamber?
  - The fundamental vertex is already poorly modelled

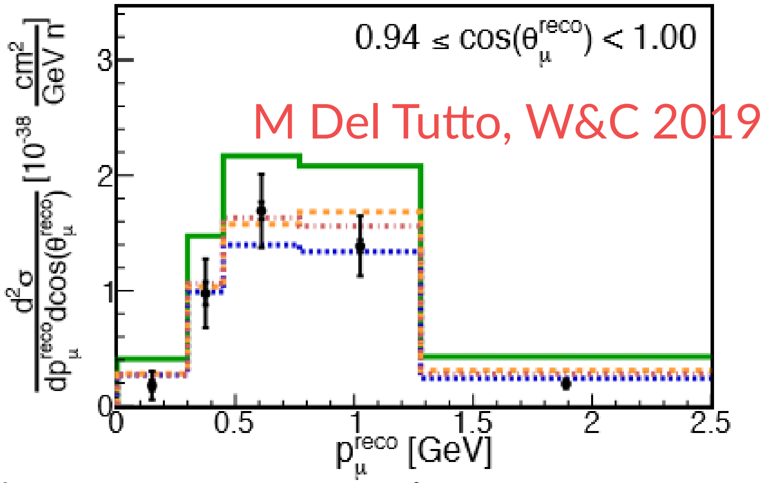
What's next?

- Will only know how good the ^{40}Ar models are with data

MicroBooNE CC-inclusive

(Although be aware, MINERvA and NOvA heavily modify their GENIE v2!)

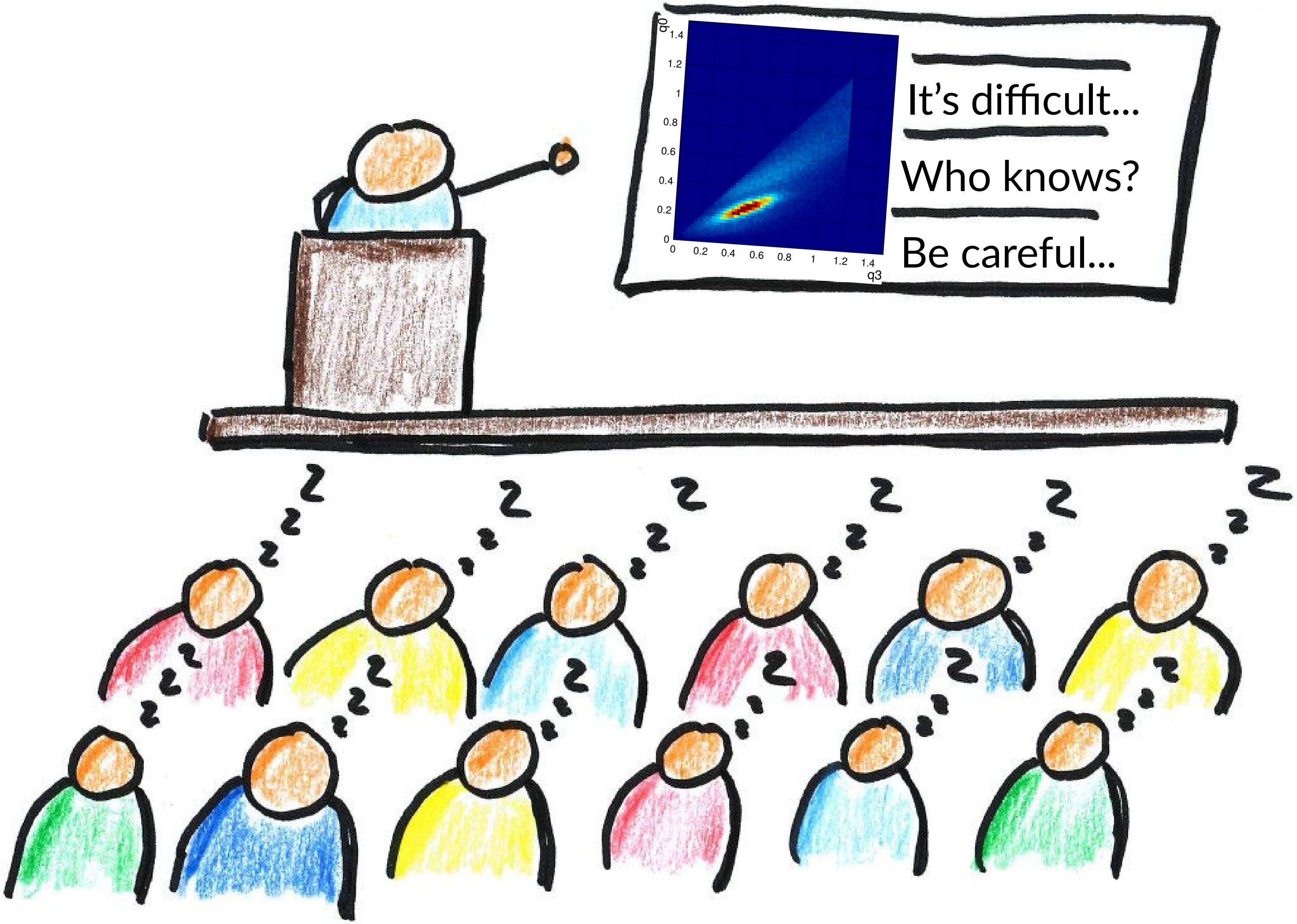
Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5



- MicroBooNE and DUNE are developing systematics dedicated to ^{40}Ar uncertainties
  - Enjoy the DUNE TDR responsibly!
- A large survey of external data is probably due
- Increase in cross-experiment cross-generator workshops is helping a lot
  - e.g. T2K using MINERvA tune, NOvA using T2K tune, comparing NOvA and MINERvA 2p2h

Conclusions

- Pfwoah, 50 minutes on interaction systematics, well done audience!



Conclusions

- Current state: there are unknown unmodelled nucleon and nuclear effects, tread carefully
- Be paranoid about your generator(s)
  - They probably won't go through your data, so be prepared
- Think critically about your measurement and develop interaction systematics accordingly
  - There is no "one size fits all" solution, yet
  - Can external data help you?
- Discuss with your cross-experiment colleagues, FNAL is an excellent place for this

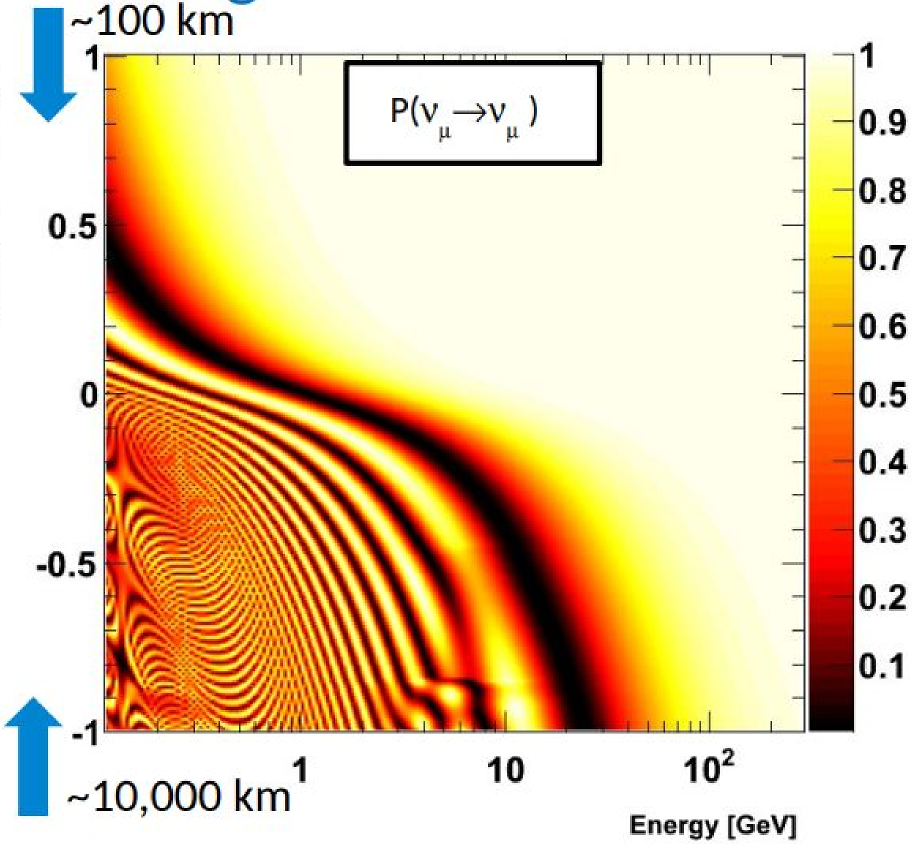
- Lots of progress continues to be made, but the end is nowhere in sight
- But hey, solid job security!

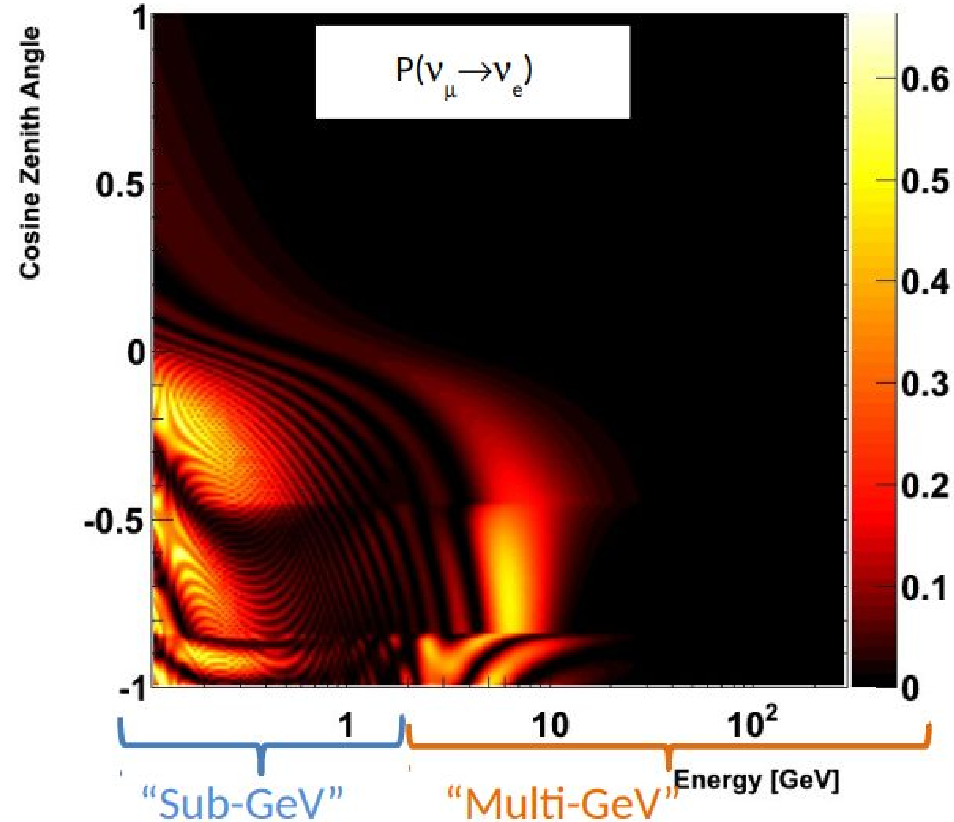
Thanks for listening!

Backups

SK

Searching for Three-Flavor Effects: Oscillation probabilities

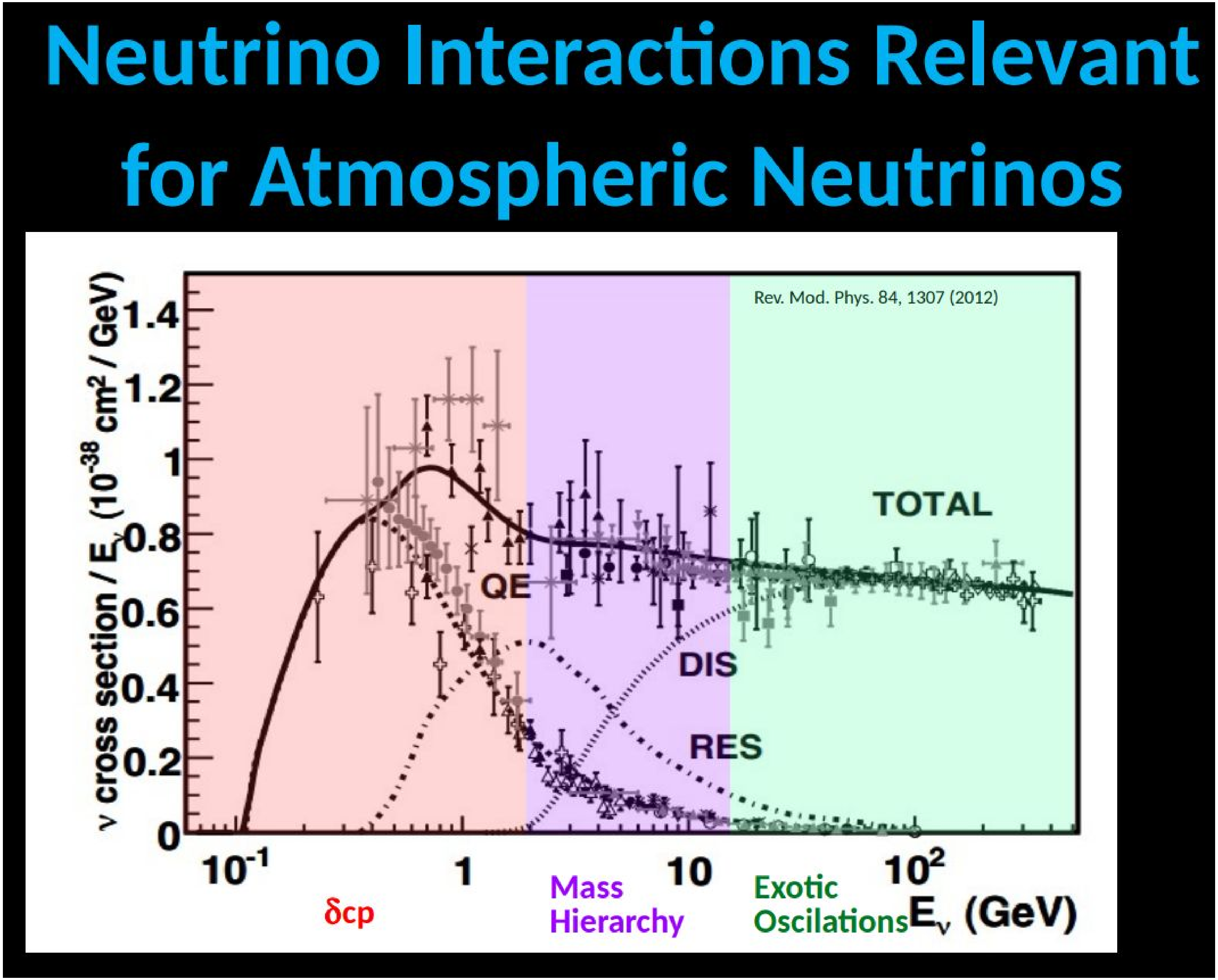




- Key Points
  - No $\nu_\mu \to \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest in upward-going ν_e

C. Bronner NuSTEC 2018 Roger Wendell, NuInt15

SK

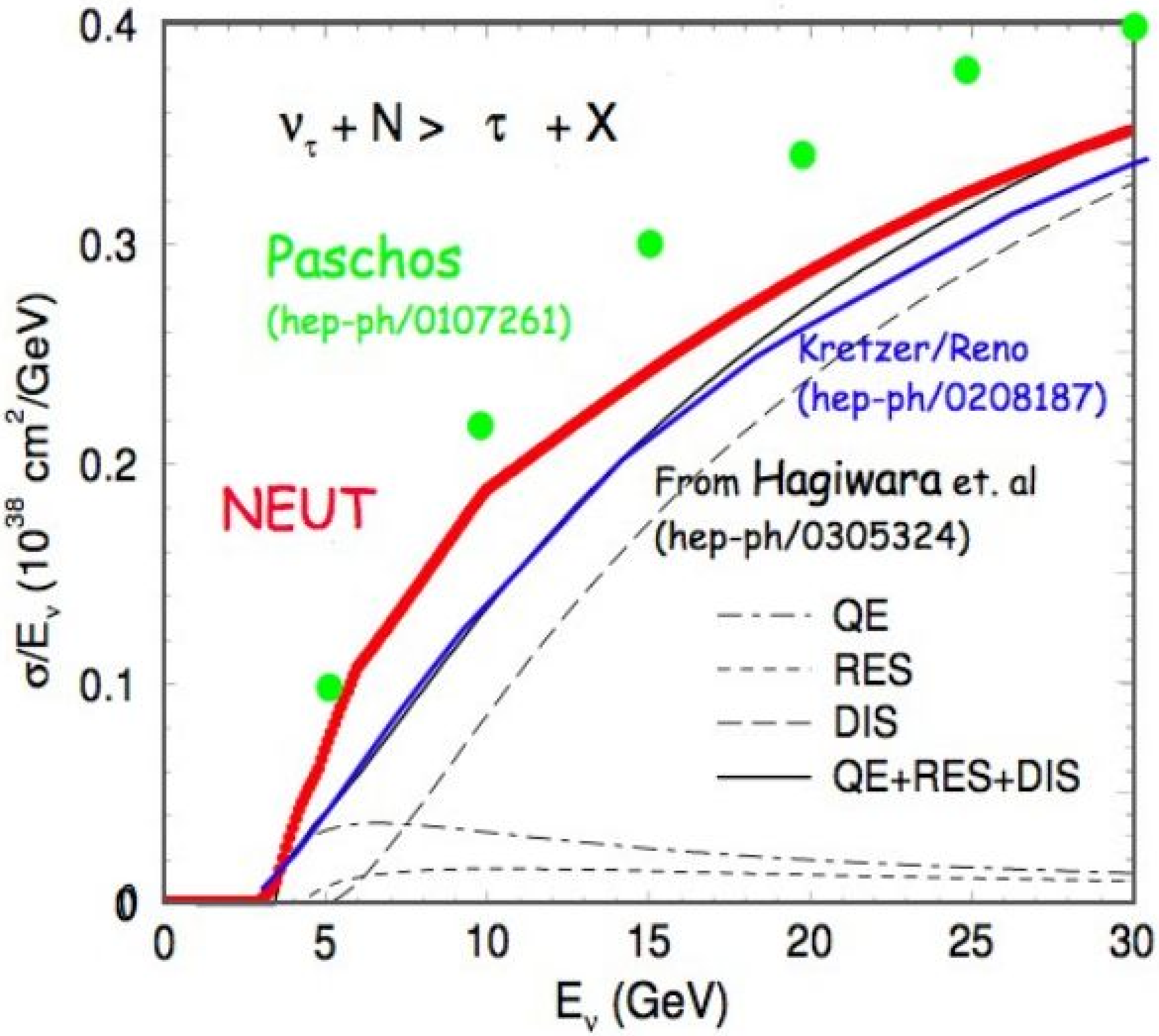


C. Bronner NuSTEC 2018

Roger Wendell, NuInt15

SK

- Hadronic tau events are large background for high energy DIS events, which have sensitivity to mass hierarchy
  - Assigned 25% uncertainty to ν_τ events



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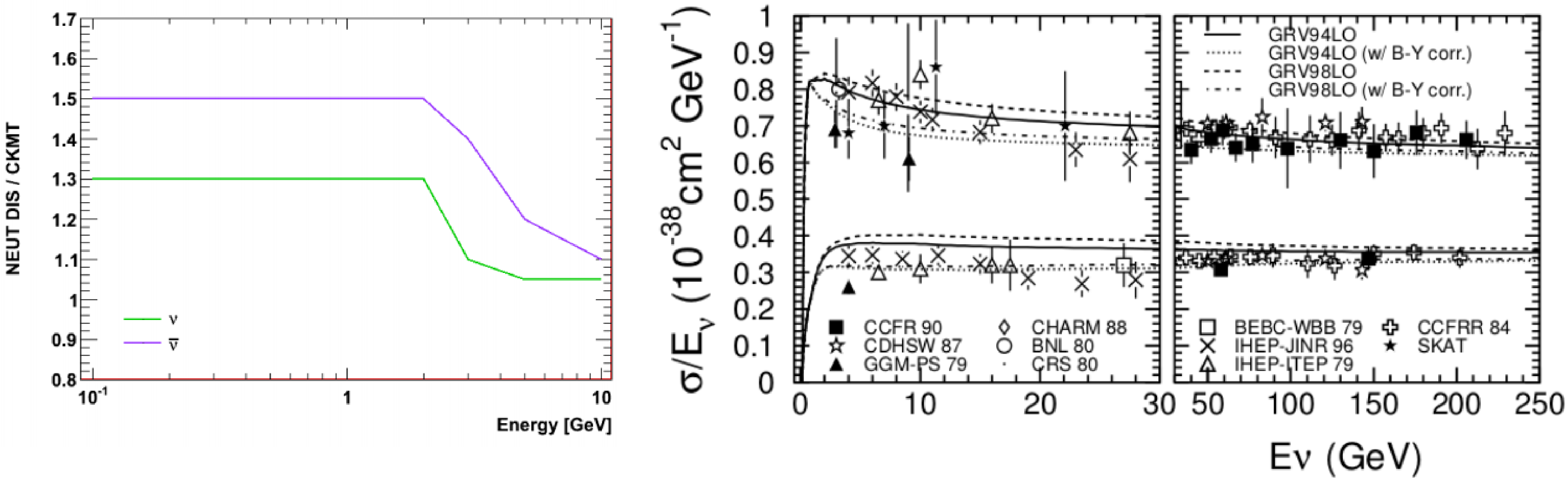
SK

Deep Inelastic Scattering

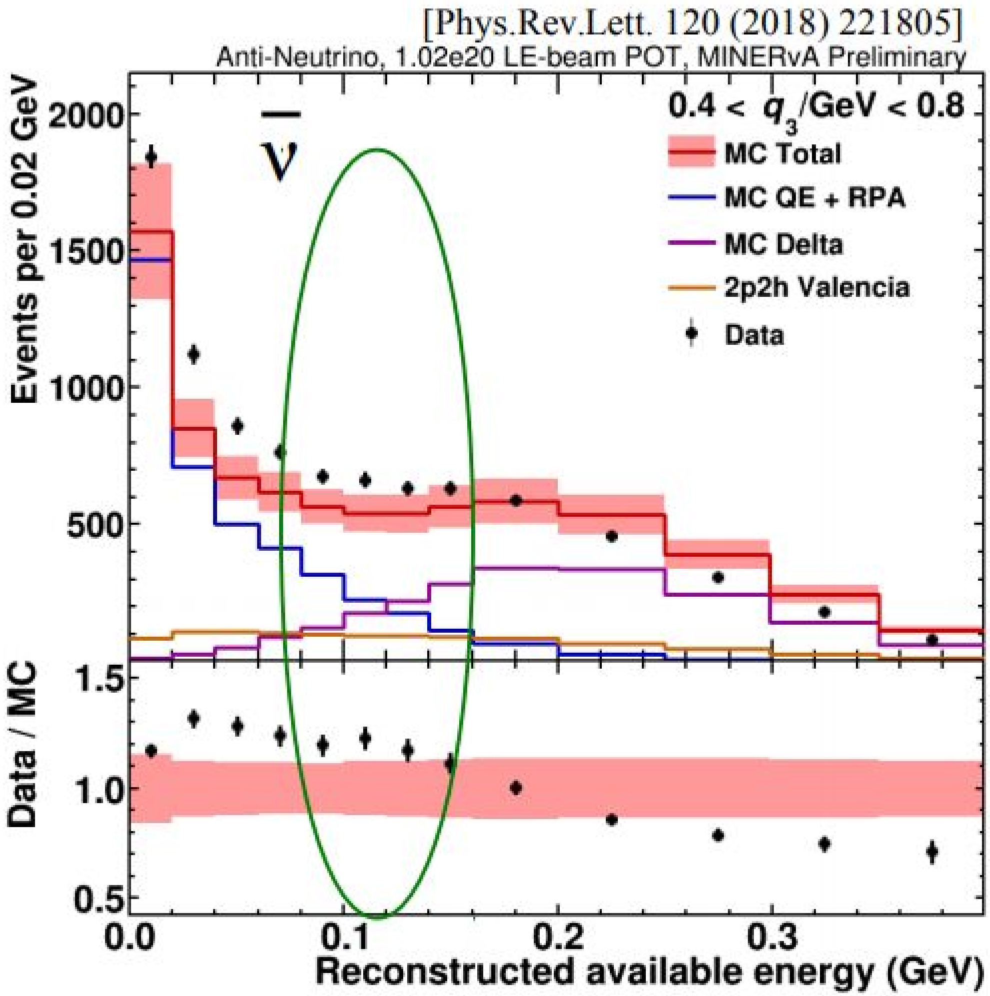


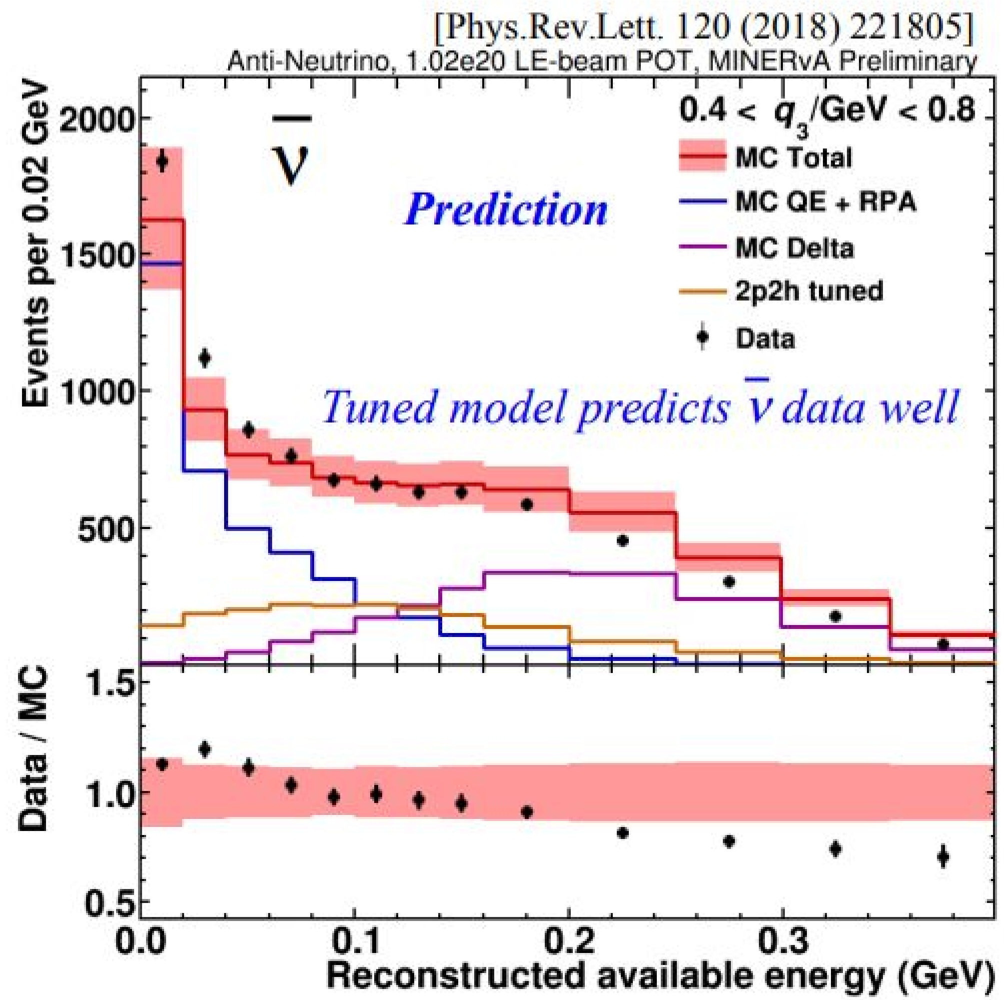
- DIS Cross section systematics are taken from comparison of the default NEUT model with the “CKMT” parameterization below 10 GeV
  - Difference between these two model ranges from 10~50%

- In addition an overall 5% normalization uncertainty is assumed at all energies

MINERvA

- Additionally enhances anti-neutrino adequately

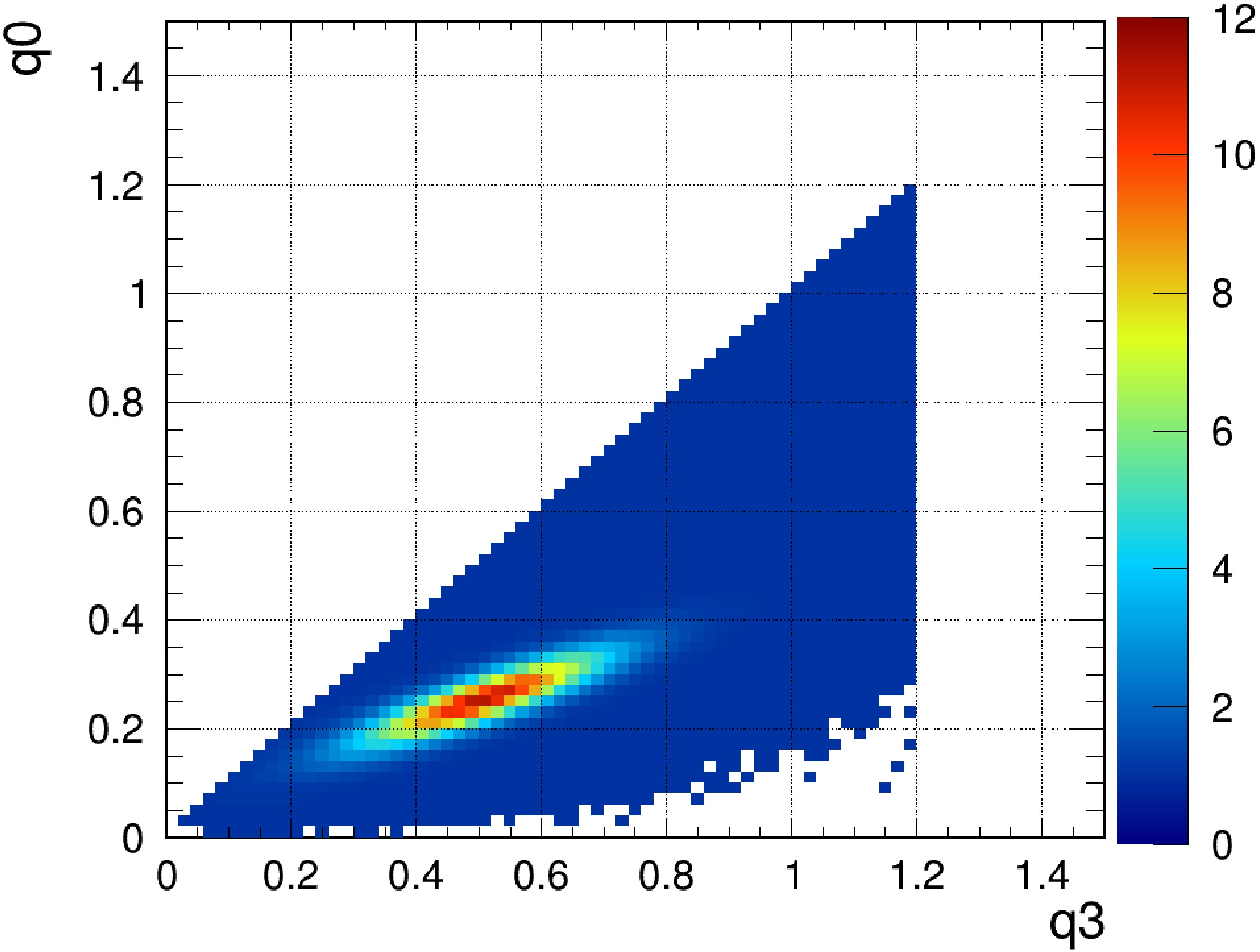




MINERvA 1pi tune R. Gran, NuInt17 X-G Lu, NuInt18

MINERvA

- The 2p2h q_0 q_3 tune



MINERvA 1pi tune R. Gran, NuInt17 X-G Lu, NuInt18

MicroBooNE

- MicroBooNE are ramping up cross-section publications
- CC0πNp uses GENIE and alternative theory-motivated GENIE production to study e.g. efficiency corrections
- Published CC1π0 and CC-inclusive use GENIE production with multi-sim approach for reweightable systematics, similar to MiniBooNE
- Are in the process of developing ^{40}Ar dedicated systematics (e.g. accounting for untested ^{12}C→^{40}Ar scaling), and surveying the global external data