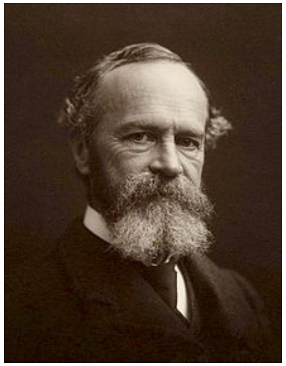
Building a cross section model for NOvA:

philosophy and implementation



"There is only one thing a philosopher can be relied upon to do, and that is to contradict other philosophers" – William James

Jeremy Wolcott
Tufts University

April 23, 2018
Fermilab NPC Seminar

Tufts UNIVERSITY

NOvA

Goal of this talk

Continue the discussion about ν cross section models and their usage based on our "test case" (NOvA)

Some questions you might ponder as I go:

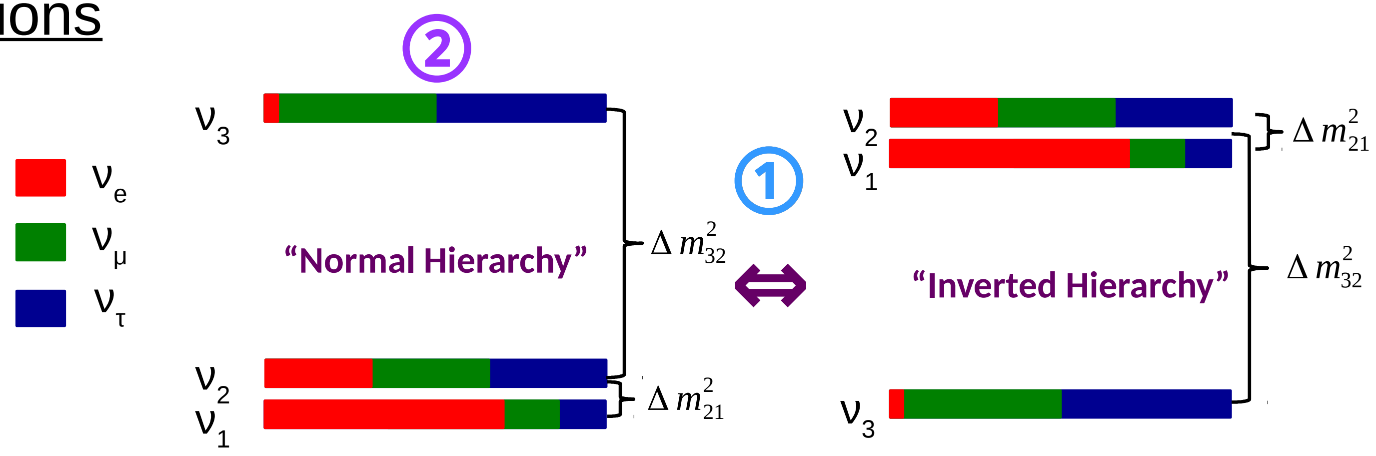
- What parts of the models used by oscillation experiments are **vulnerable to producing incorrect results** because they're incomplete or are tuned to out-of-date data?
- What sort of **empirical modifications** to those models are reasonable?
- Can we (collectively) make better **prioritizations about efforts to implement models** into generators?
- Are we (as a community) constructing **"safe" uncertainties** to use for neutrino oscillation work?

The NOvA experiment: program

- Engaging major questions in oscillation physics:

  ① How are the mass eigenstates ordered?

  ② Is there a symmetry governing mixing between ν_μ and ν_τ?



② ③

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

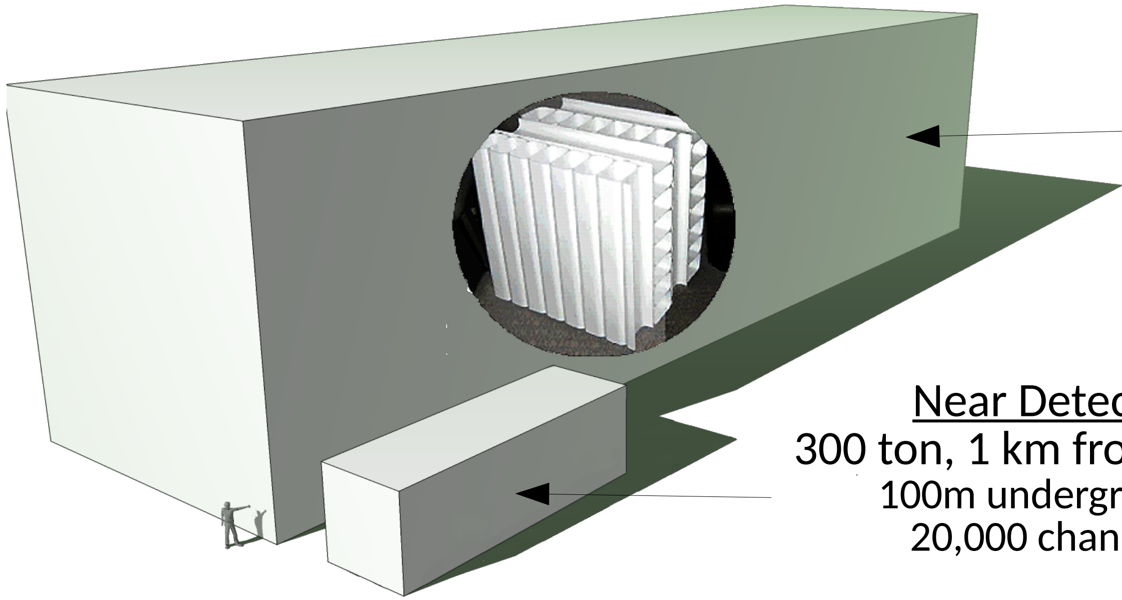
③ Is there CP violation in leptons?

- Searching beyond the Standard Model:

Are there more than 3 neutrino states?
Can we observe dark matter via decays to leptons?
Do magnetic monopoles exist?
...

- Neutrino cross section measurements

The NOvA experiment: two detectors



Far Detector
14 kton, 810 km from source
On the surface
(3m concrete+barite overburden)
344,000 channels

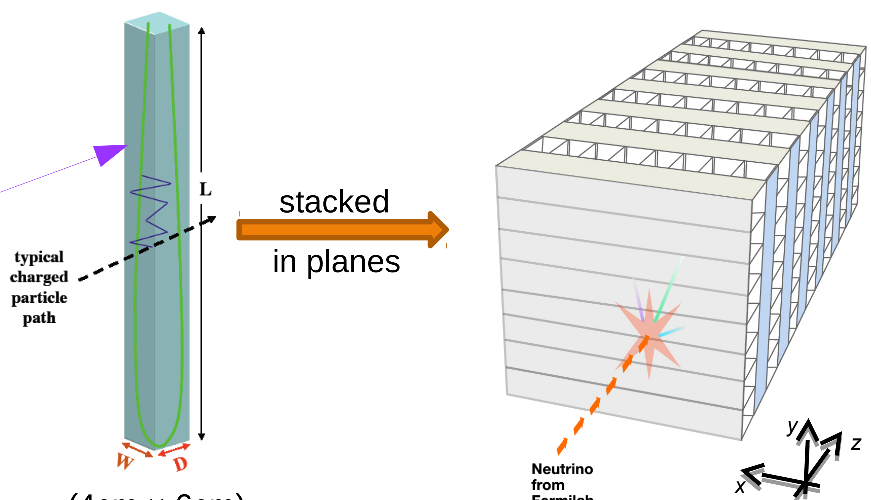
Near Detector
300 ton, 1 km from source
100m underground,
20,000 channels

Functionally identical detectors

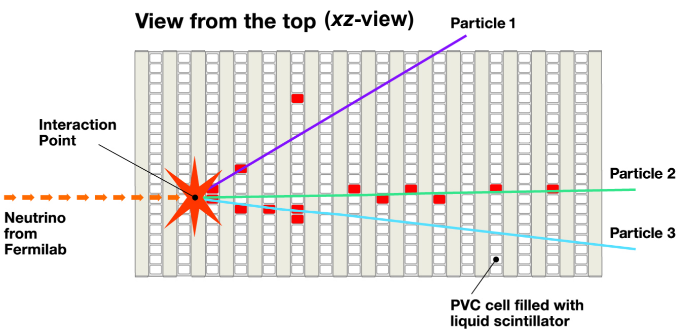
Sampling calorimeter detectors

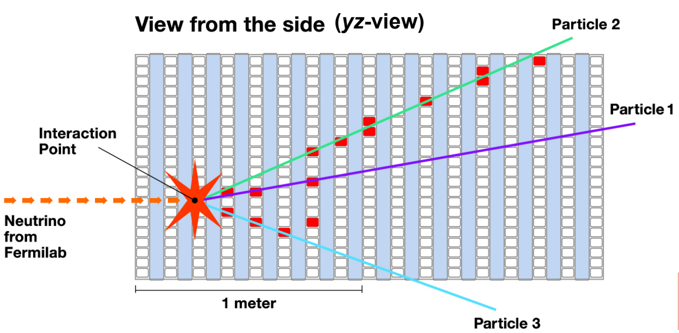
Filled with CH_2

1 Channel



(4cm × 6cm)

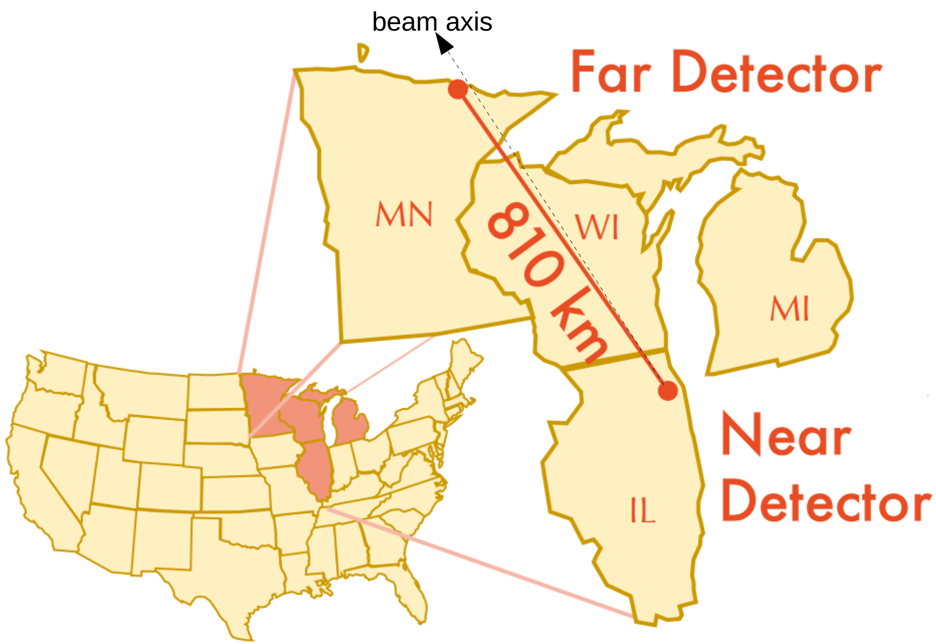


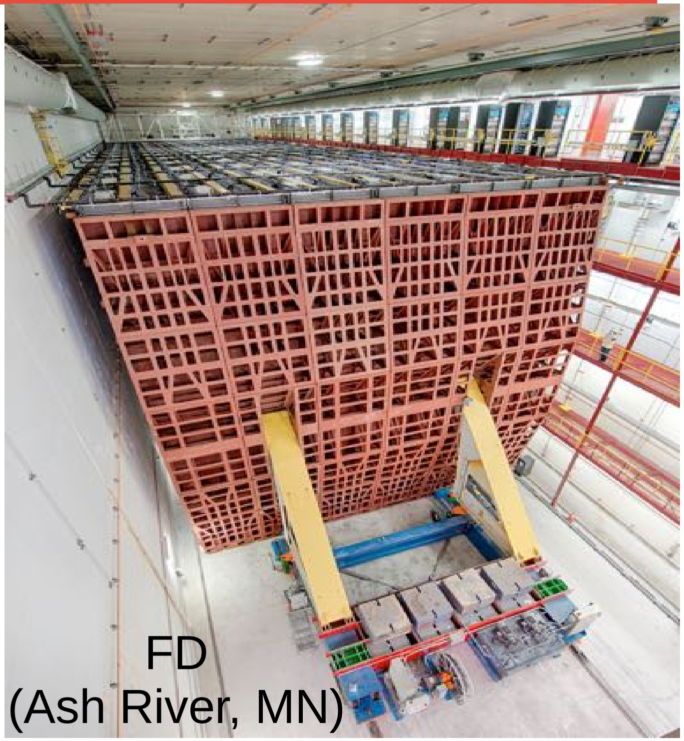


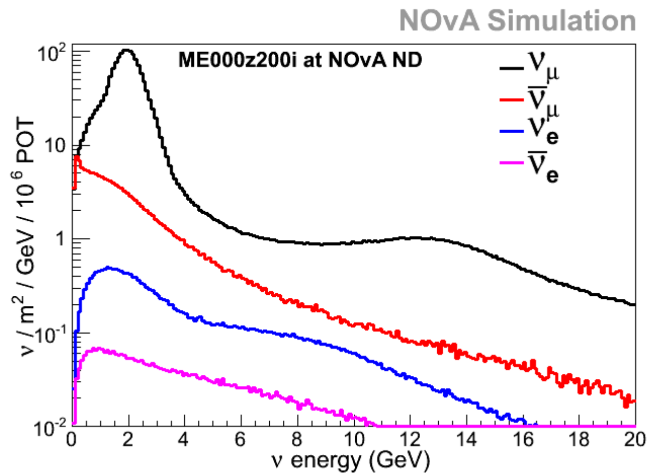
J. Wolcott / Tufts

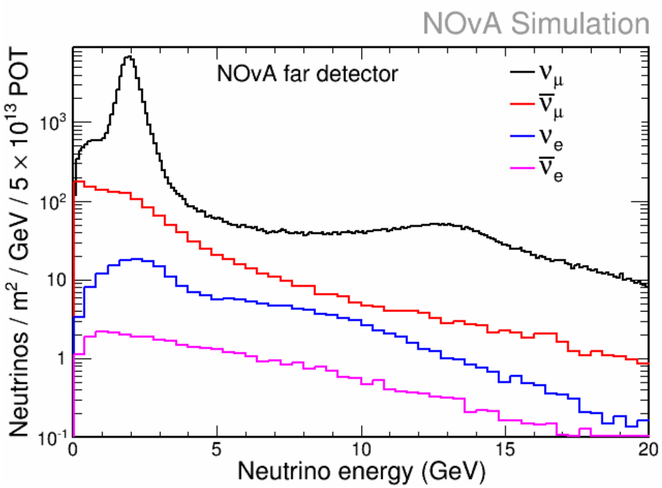
The NOvA experiment: beam

14.6mrad off-axis beam results in narrow-band beam around 2 GeV (but non-negligible tail)

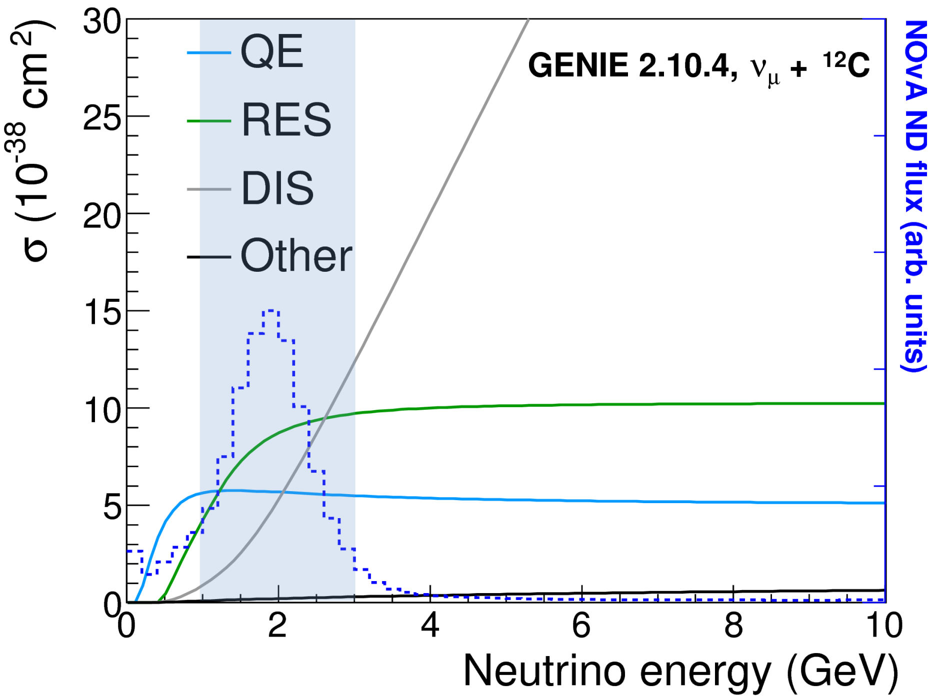




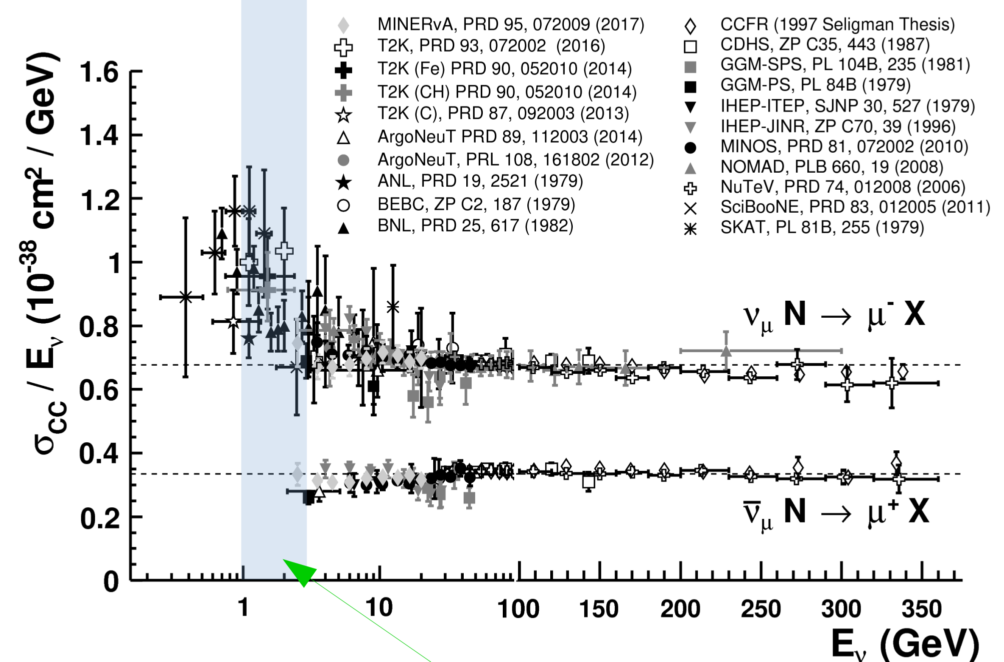




Cross section model: interests



[PDG: Chin. Phys. C40, 100001]



(…oh, and not constrained very well either…)

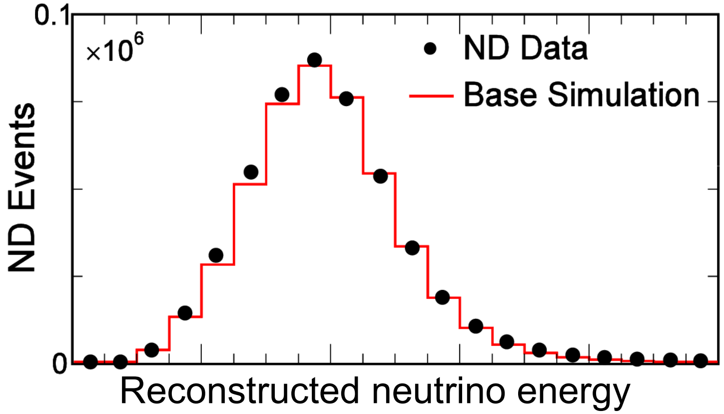
So… cross sections of most interest:

- CC reactions on hydrogen, carbon ~1-3 GeV
- NC reactions on hydrogen, carbon up to at least 10 GeV
- Both ν and $\bar{\nu}$

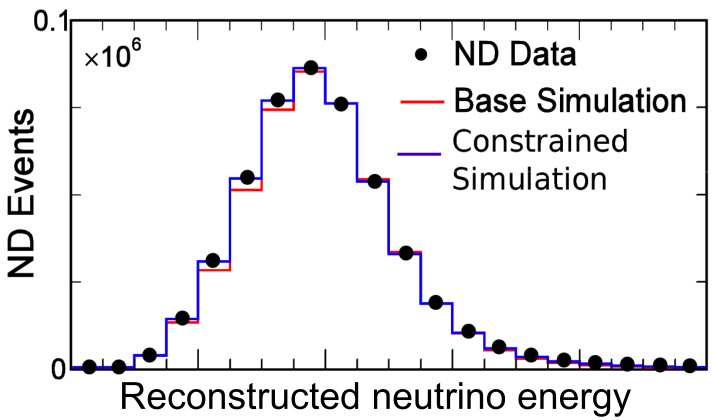
A delightful mix of everything!

(with no convenient limits for approximations)

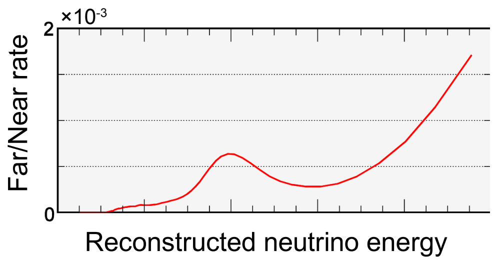
The NOvA experiment: oscillation strategy

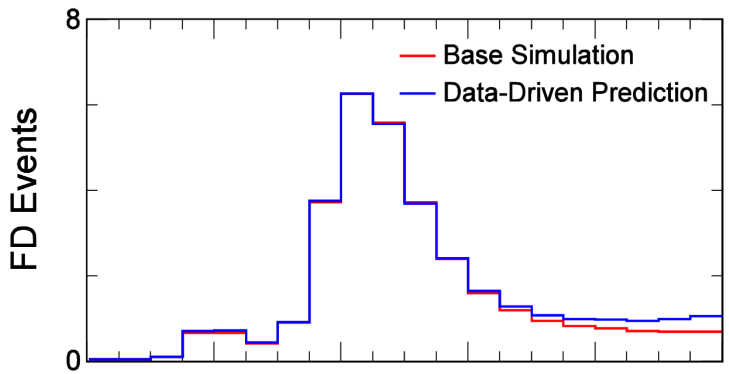


Constrain underlying true spectrum



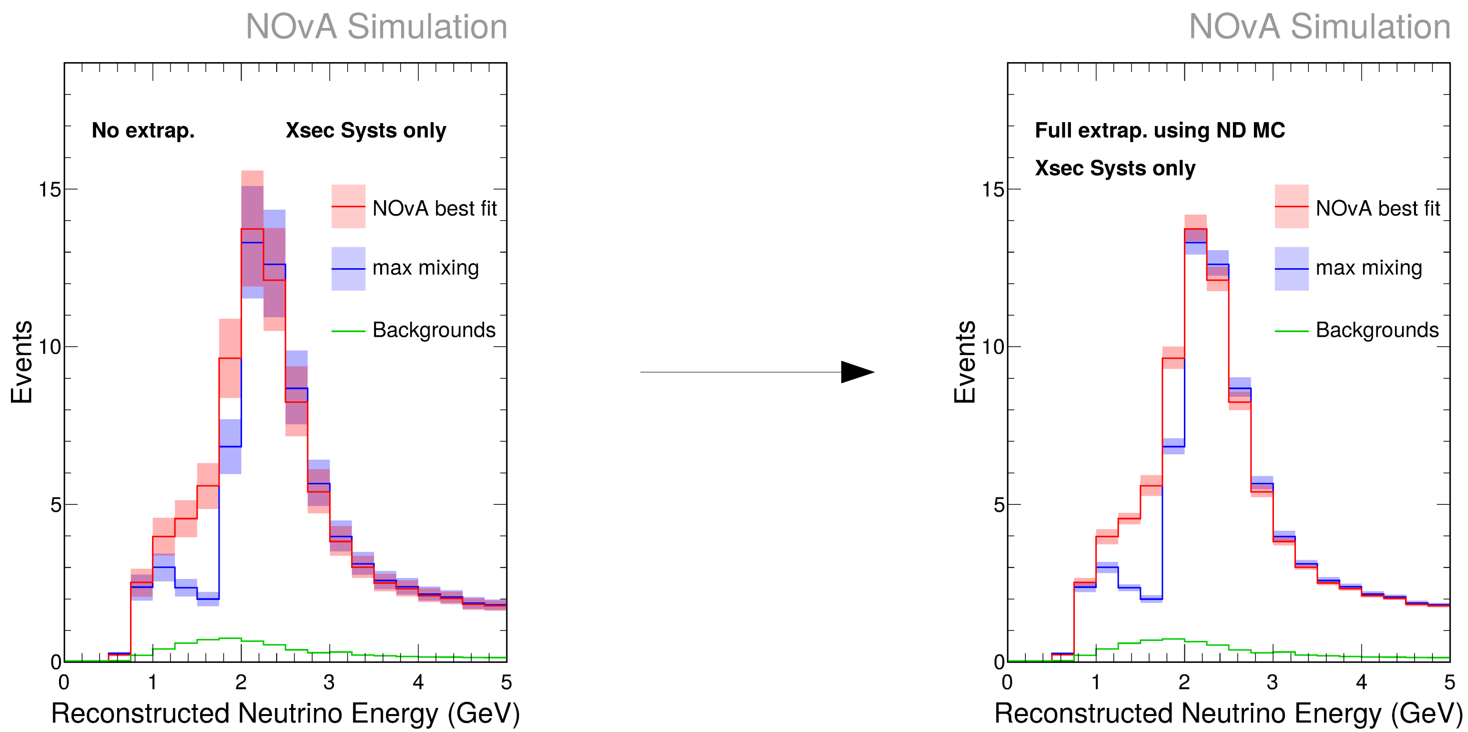
"Extrapolated" using beam divergence, geometric differences from simulation (plus oscillations)





Why we have two detectors

The NOvA experiment: oscillation strategy

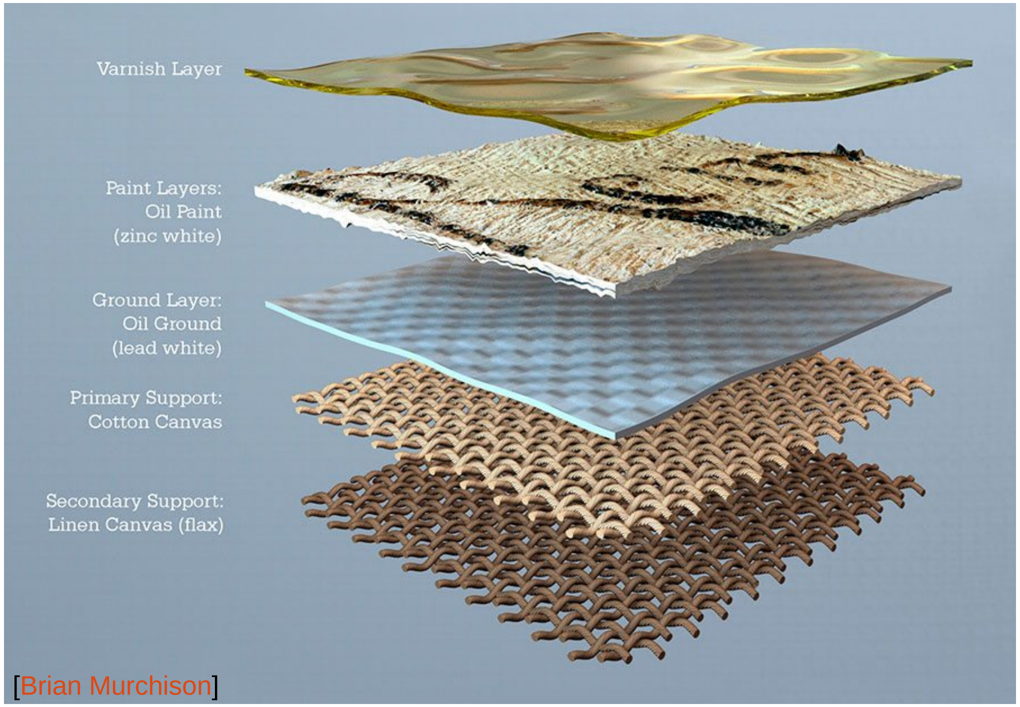


Extrapolation substantially reduces
(but doesn't entirely eliminate)
effect of most cross section uncertainties

So, don't panic (yet)...
but subtleties are important for
precise oscillation results

Base model philosophy

GENIE's cross section model is kind of like a layer painting:



Glaze: **rare processes**
- Pure leptonic: ν+e, inv. μ decay
- (Heavy) flavor modifications to below

Overlayer: **“nuclear effects”**
- Initial-state effects (Fermi mom., Pauli blocking, SRC; shadowing/antishadowing, EMC, ...)
- Multibody operators (MEC)
- Collective excitations (Giant resonances, screening; diffractive)
- Final-state interactions

Substrate: **single nucleon** processes
- Elastic (e.g. $\nu_\mu N \to \mu N'$)
- Baryon resonance production (e.g. $\nu_\mu N \to \mu \Delta \to \mu N \pi$)
- Inelastic continuum (SIS/transition, DIS)

Base model philosophy

A painting is no better than its canvas...

[Valerie Hagerty]

<u>Glaze</u>: **rare processes**
- Pure leptonic: ν+e, inv. μ decay
- (Heavy) flavor modifications to below

<u>Overlayer</u>: **"nuclear effects"**
- Initial-state effects (Fermi mom., Pauli blocking, SRC; shadowing/antishadowing, EMC, ...)
- Multibody operators (MEC)
- Collective excitations (Giant resonances, screening; diffractive)
- Final-state interactions

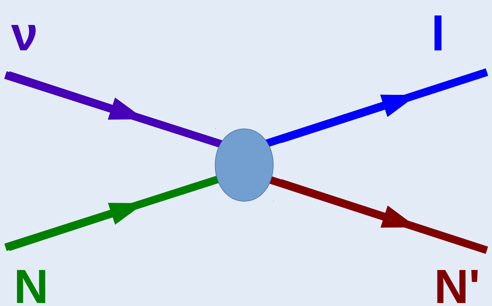
<u>Substrate</u>: **single nucleon** processes
- Elastic (e.g. ν_μ N → μ N')
- Baryon resonance production (e.g. ν_μ N → μ Δ → μ N π)
- Inelastic continuum (SIS/transition, DIS)

Base model: single nucleon

We use GENIE (v2.12.2) as our interaction generator. Basic models:

(Quasi-)elastic

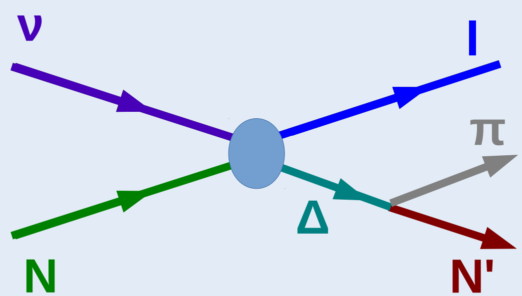
"Llewellyn Smith" model



Baryon resonance

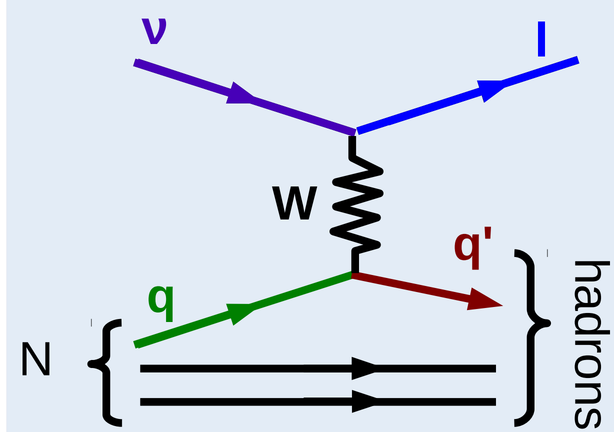
D. Rein

"Rein-Sehgal" model



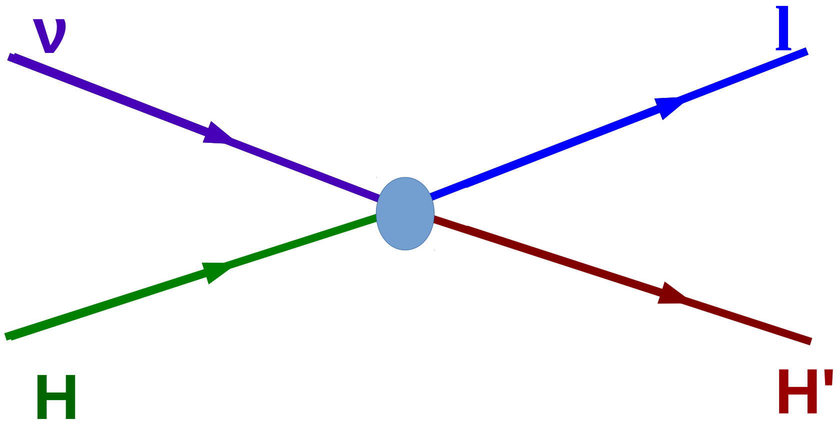
Inelastic continuum

"Bodek-Yang" model

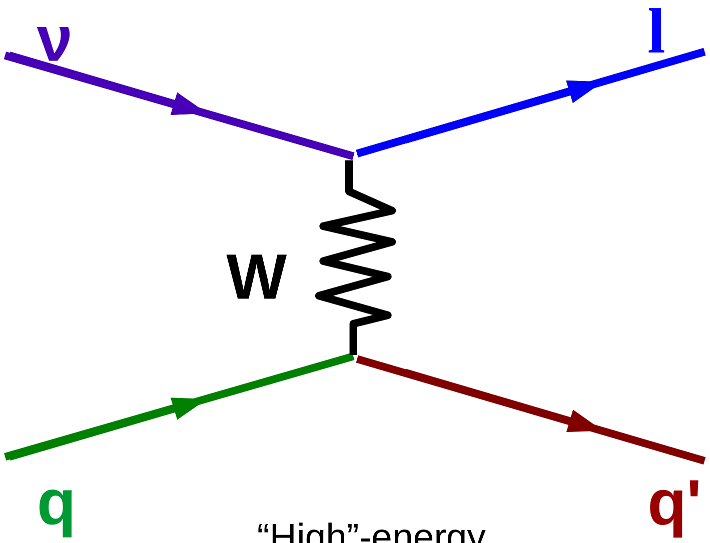


More energy transferred to hadronic system

Base model: ingredients



"Low"-energy
(react w/ nucleons; mesons mediate)



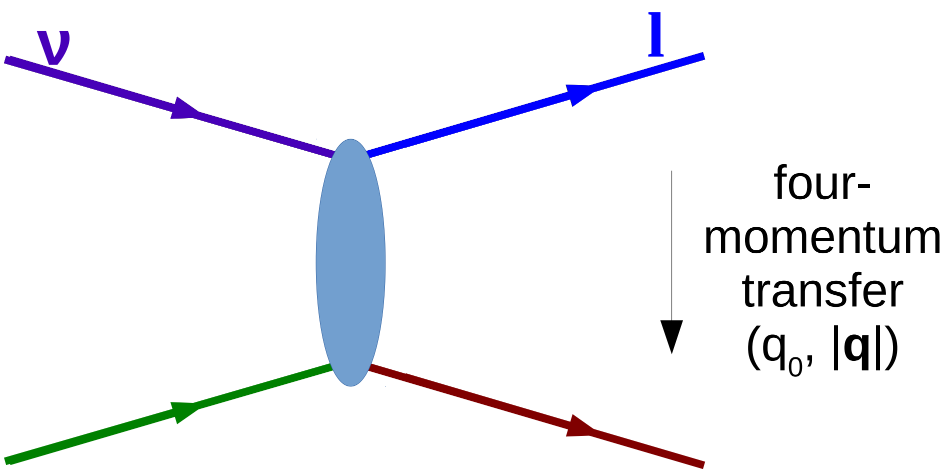
"High"-energy
(react w/ partons; gluons mediate)

Basic idea

Lepton end can be calculated exactly (at tree level anyway);
Parameterize the hadron end appropriately depending on the relevant momentum scale

(For "low-energy": "current-current" interaction, effective 4-point interaction like Fermi theory; parton model uses W propagator directly)

Base model: ingredients



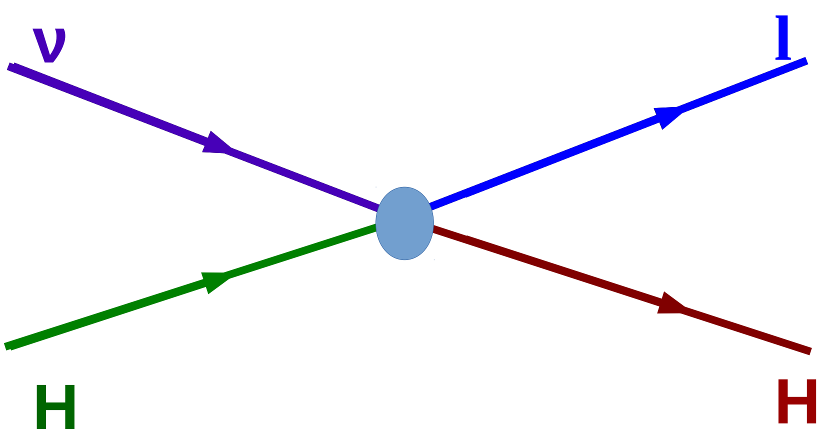
Whatever your picture, there's some common nomenclature I'll use repeatedly:

$$Q^2 = -q^2 = -(q^\mu q_\mu)$$
$$= |\vec{q}|^2 - q_0{}^2$$

q_0 → "energy transfer"

$|\vec{q}|$ → "three-momentum transfer"
(or sometimes q_3)

Base model: ingredients



[Phys. Rep. 3C, 261]

$$\frac{d\sigma}{dQ^2}\binom{\nu n\to l^- p}{\bar{\nu} p\to l^+ n} = \left[A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right] \times \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2} \qquad (4)$$

$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\Bigg[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\xi|F_V^2|^2\left(1-\frac{Q^2}{4M^2}\right) + \frac{4Q^2 Re F_V^{1*}\xi F_V^2}{M^2} - \frac{Q^2}{M^2}\left(4+\frac{Q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1+\xi F_V^2|^2 + |F_A+2F_P|^2 - \left(4+\frac{Q^2}{M^2}\right)\left(|F_V^3|^2+|F_P|^2\right)\right)\Bigg],$$

$$B(Q^2) = \frac{Q^2}{M^2} Re F_A^*\left(F_V^1+\xi F_V^2\right) - \frac{m^2}{M^2} Re\left[\left(F_V^1 - \frac{Q^2}{4M^2}\xi F_V^2\right)^* F_V^3 - \left(F_A - \frac{Q^2 F_P}{2M^2}\right)^* F_A^3\right] \text{ and}$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2+|F_V^1|^2+\frac{Q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 + \frac{Q^2}{M^2}|F_A^3|^2\right).$$

Parameterizations usually in terms of *form factors* (all the F_*), which are functions of Q^2

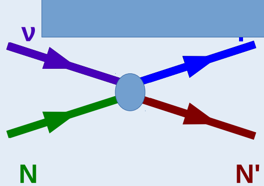
Base model: single nucleon

We use GENIE (v2.12.2) as our interaction generator:

Elastic

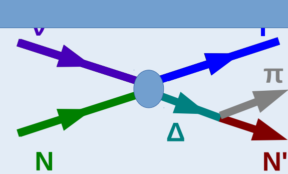
“Llewelly

- Hadroni
  paramet
  factors
- Most FF
  external
  parity ar
  FF: mus
  scatterin
  - Dipol
    assu



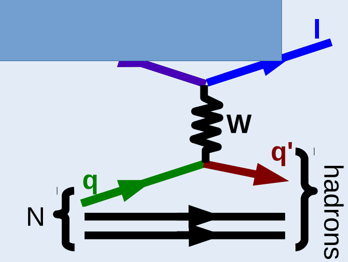
Baryon resonance

D. Rein



Inelastic continuum

l:
quark
d
ng
for



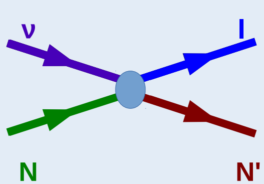
Even in the 'simple' (free nucleon) case everything is not so simple…

Base model: single nucleon

Elastic

"<u>Llewellyn Smith</u>" model:

- Hadronic current contraction parameterized in terms of *form factors*
- Most FFs constrained from external data or assumed via parity arguments except *axial* FF: must be measured from ν scattering
  - <u>Dipole</u> structure historically assumed...



$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \right.$$
$$-\frac{Q^2}{M^2}\left(4+\frac{Q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1+\xi F_V^2|^2 + \right.$$

$$B(Q^2) = \frac{Q^2}{M^2} Re F_A^*(F_V^1+\xi F_V^2) - \frac{m^2}{M^2} Re\left[\left(F_V^1 - \frac{Q^2}{4M^2}\xi F_V^2\right.\right.$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 + \frac{Q^2}{M^2}|F_A^3|^2\right).$$

The axial form factor traditionally assumed dipole:

$$F_A(Q^2) = F(0)\left(1+\frac{M_A^2}{Q^2}\right)^{-2}$$

(Measure in free nucleon scattering expt)

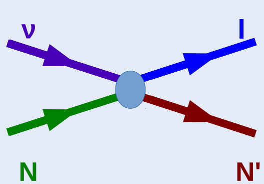
(Fixed in pion decay)

Base model: single nucleon

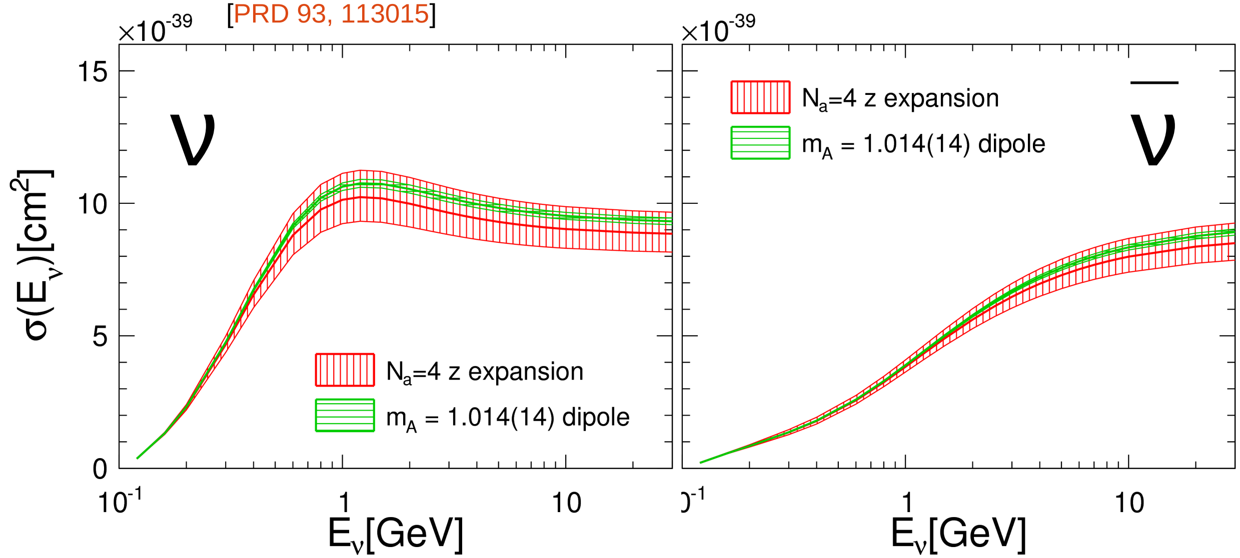
Elastic

"<u>Llewellyn Smith</u>" model:

- Hadronic current contraction parameterized in terms of *form factors*
- Most FFs constrained from external data or assumed via parity arguments except *axial* FF: must be measured from ν scattering
  - <u>Dipole</u> structure historically assumed...



[PRD 93, 113015]



But...

The dipole shape of the axial FF is just an *ansatz*.

When you use a more general form,
the answer (esp. the uncertainties) changes!

[Current NOvA results use dipole with $M_A = 1.04 \pm 0.05$;
will switch to z-exp in future]

Base model: single nucleon

[PRD 3, 2706]

Current Matrix Elements from a Relativistic Quark Model*

R. P. Feynman, M. Kislinger, and F. Ravndal
Lauritsen Laboratory of Physics, California Institute of Technology, Pasadena, California 91109
(Received 17 December 1970)

A relativistic equation to represent the symmetric quark model of hadrons with harmonic interaction is used to define and calculate matrix elements of vector and axial-vector currents. Elements between states with large mass differences are too big compared to experiment, so a factor whose functional form involves one arbitrary constant is introduced to compensate this. The vector elements are compared with experiments on photoelectric meson production, K_{l3} decay, and $\omega \to \pi\gamma$. Pseudoscalar-meson decay widths of hadrons are calculated supposing the amplitude is proportional (with one new scale constant) to the divergence of the axial-vector current matrix elements. Starting only from these two constants, the slope of the Regge trajectories, and the masses of the particles, 75 matrix elements are calculated, of which more than $\frac{3}{4}$ agree with the experimental values within 40%. The problems of extending this calculational scheme to a viable physical theory are discussed.

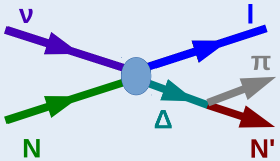
"...75 matrix elements are calculated, of which more than 3/4 agree with the experimental values within 40%."

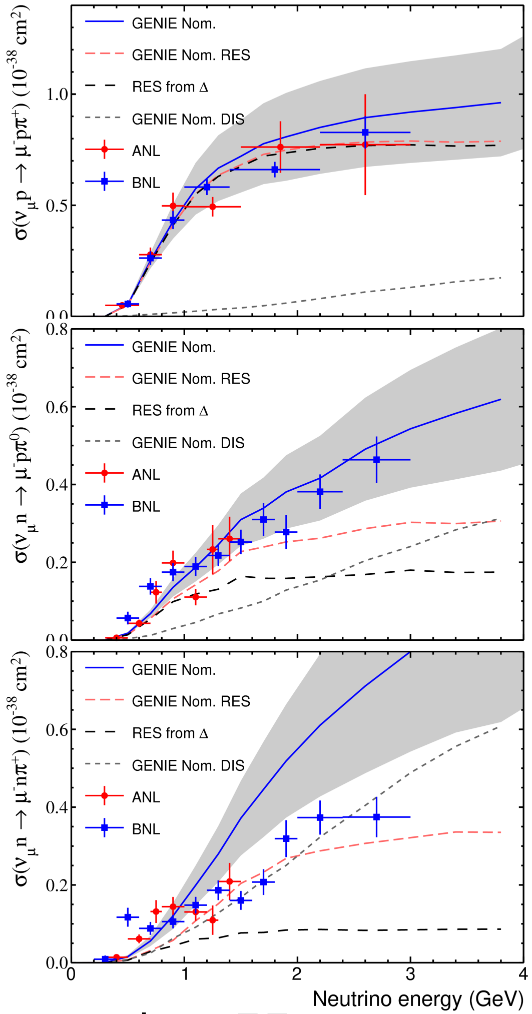
Baryon resonance

D. Rein

"Rein-Sehgal" model:

- Based on quark model from Feynman, Kislinger, Ravndal
- Amplitudes for 18 resonances (GENIE uses 16)
- Again has numerous FFs, with an axial one assumed to be dipole with parameters for ν scattering to resolve...





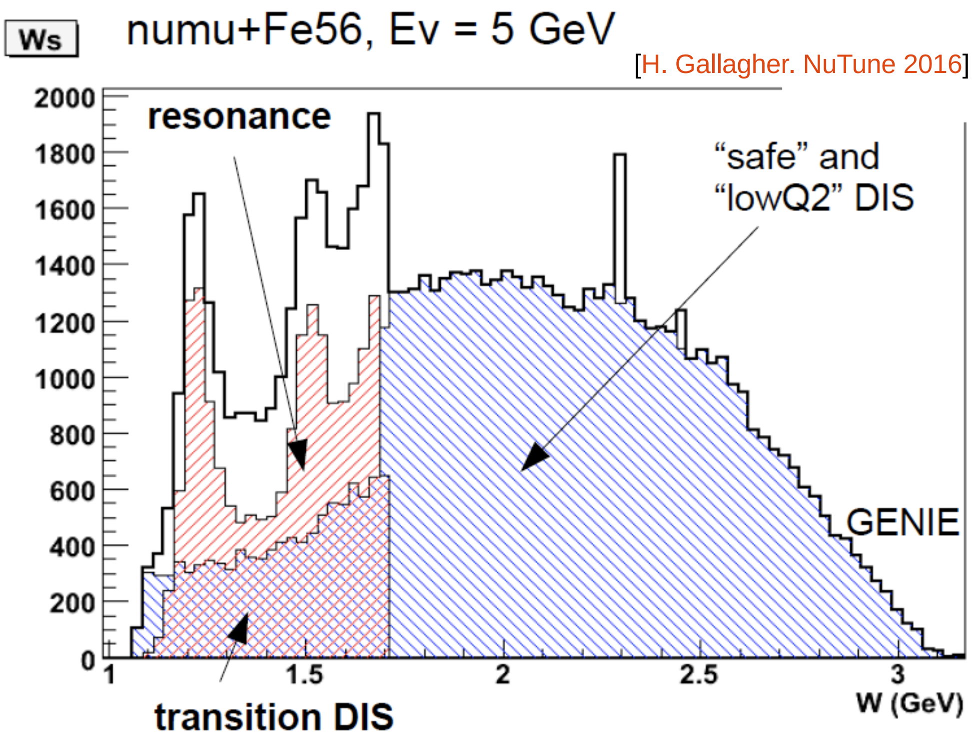
[Eur.Phys.J. C76, 474]

Extracting FF parameters nontrivial again...

(bonus: DIS model matters here too! → next slide)

[we use updated nonres bkgd from Rodrigues *et al.*]

Base model: single nucleon

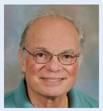


Bodek-Yang is prediction for *everything,* <u>including resonance region</u>.

Need to "stitch" together and *subtract* resonant part of B-Y to avoid double-counting. **But this doesn't correctly address interference w/ resonances**…

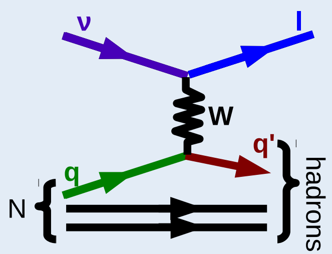
<u>Tuned to free nucleon data</u> to get total right (prev slide)… means **data quality ↔ model quality**

Inelastic continuum



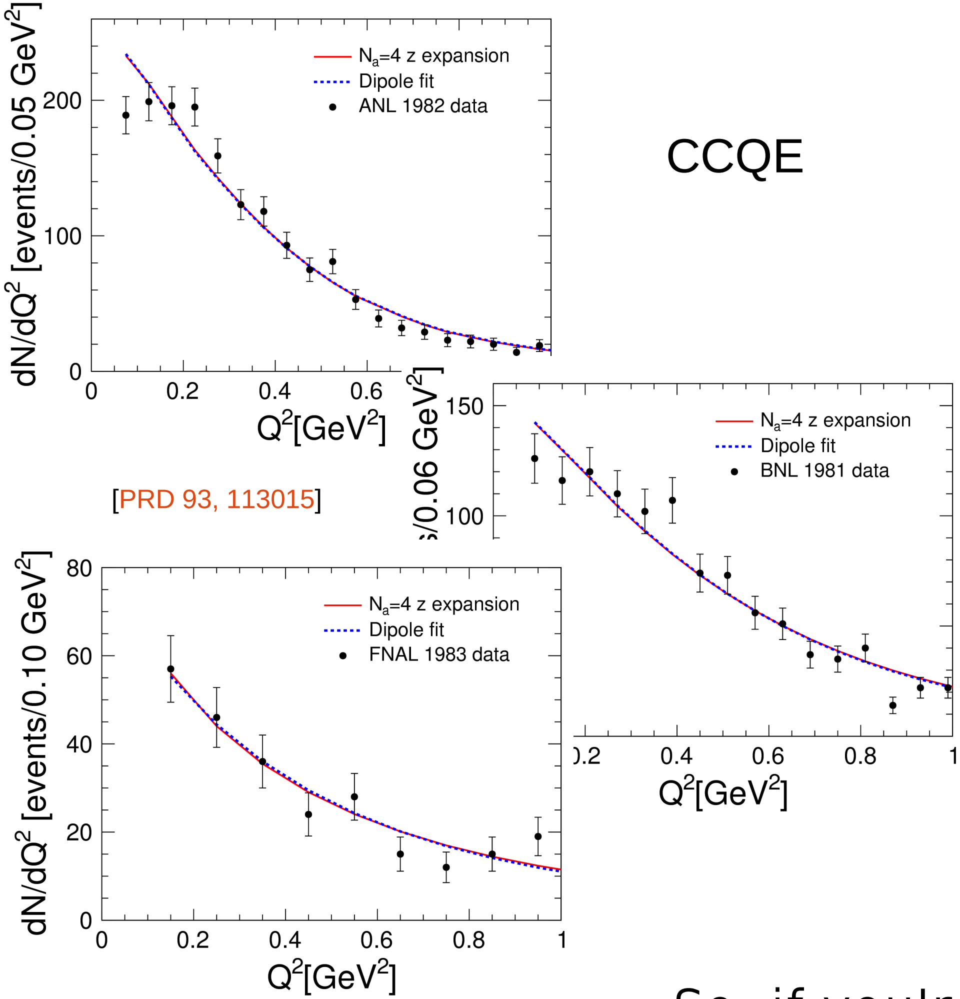
"Bodek-<u>Yang</u>" model:

- Parton model for lepton-quark scattering
- Uses externally measured nucleon PDFs
- Introduces effective scaling variables to compensate for modifications at low Q^2

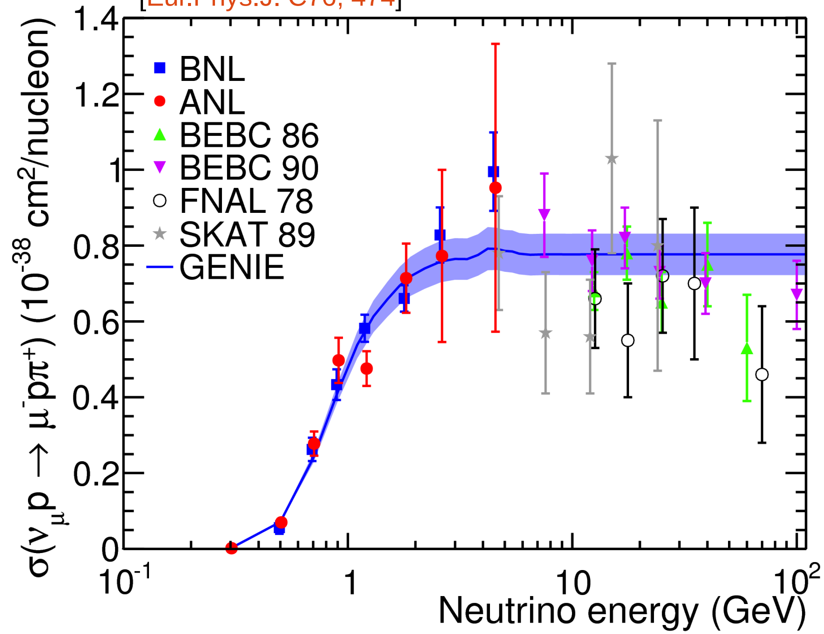


Base model: free nucleon

CCQE



1π



So, if you're keeping score:
After some massaging,
the low-energy free nucleon model
isn't doing great, but maybe okay??

Base model philosophy

If the canvas is weak, the next layer is far 'sketchier'...

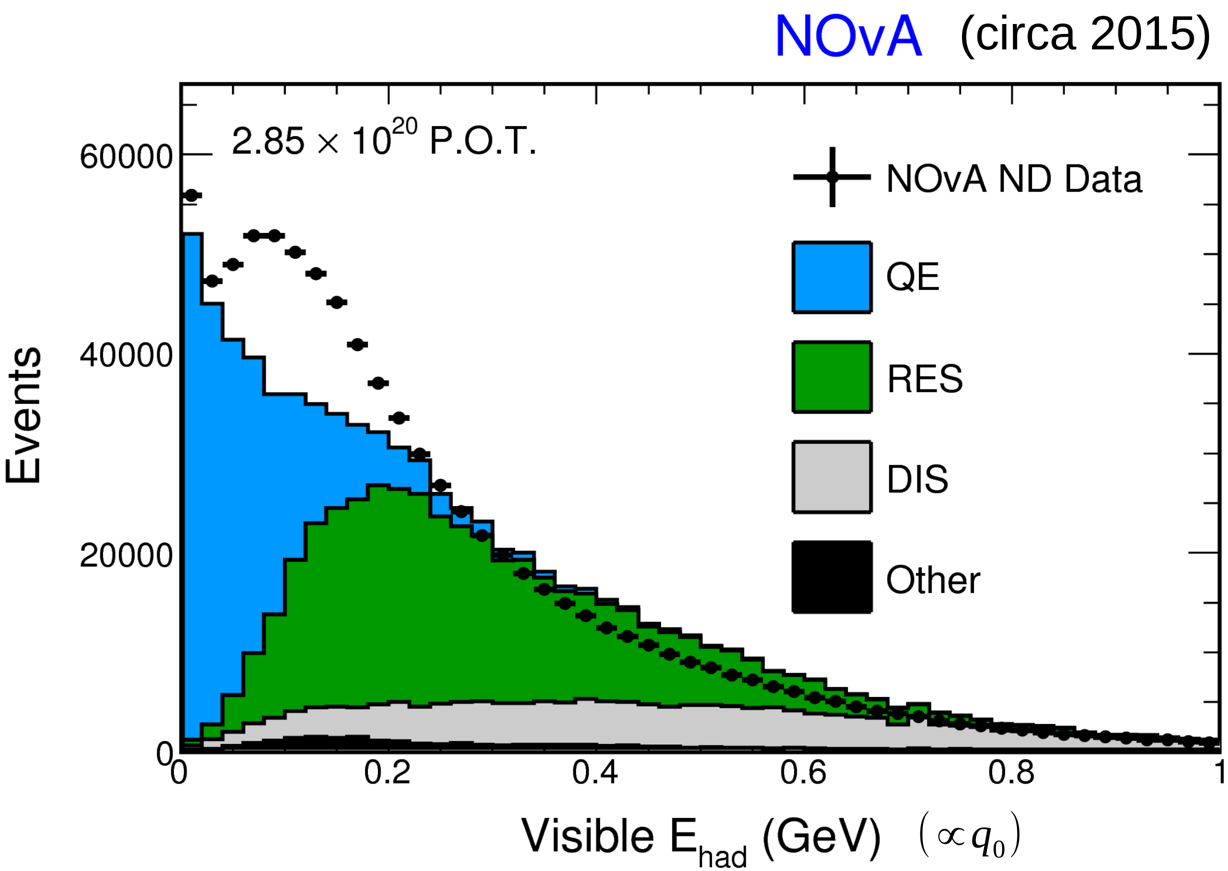
[hodgepodge.me]

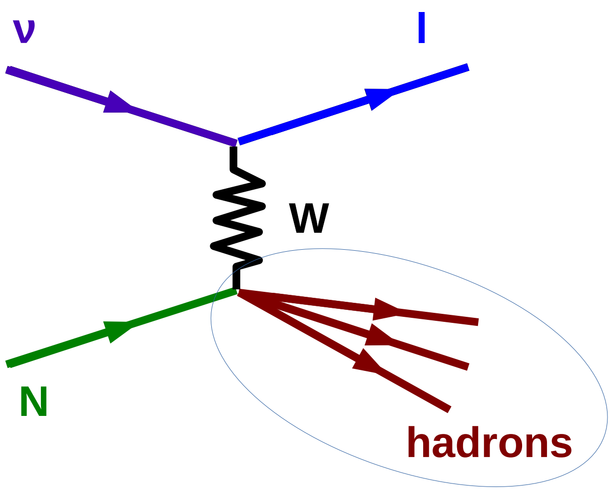
Glaze: **rare processes**
- Pure leptonic: ν+e, inv. μ decay
- (Heavy) flavor modifications to below

Overlayer: **"nuclear effects"**
- Initial-state effects
  (Fermi mom., Pauli blocking, SRC; shadowing/antishadowing, EMC, ...)
- Multibody operators (MEC)
- Collective excitations
  (Giant resonances, screening; diffractive)
- Final-state interactions

Substrate: **single nucleon** processes
- Elastic (e.g. $\nu_\mu N \rightarrow \mu N'$)
- Baryon resonance production
  (e.g. $\nu_\mu N \rightarrow \mu \Delta \rightarrow \mu N \pi$)
- Inelastic continuum (SIS/transition, DIS)

Confronting the base model with our data





Like other expts. w/ heavy targets,
we discovered early on that our simulation has notable
disagreements with our ND data

Need to adjust cross section model beyond the "base"...

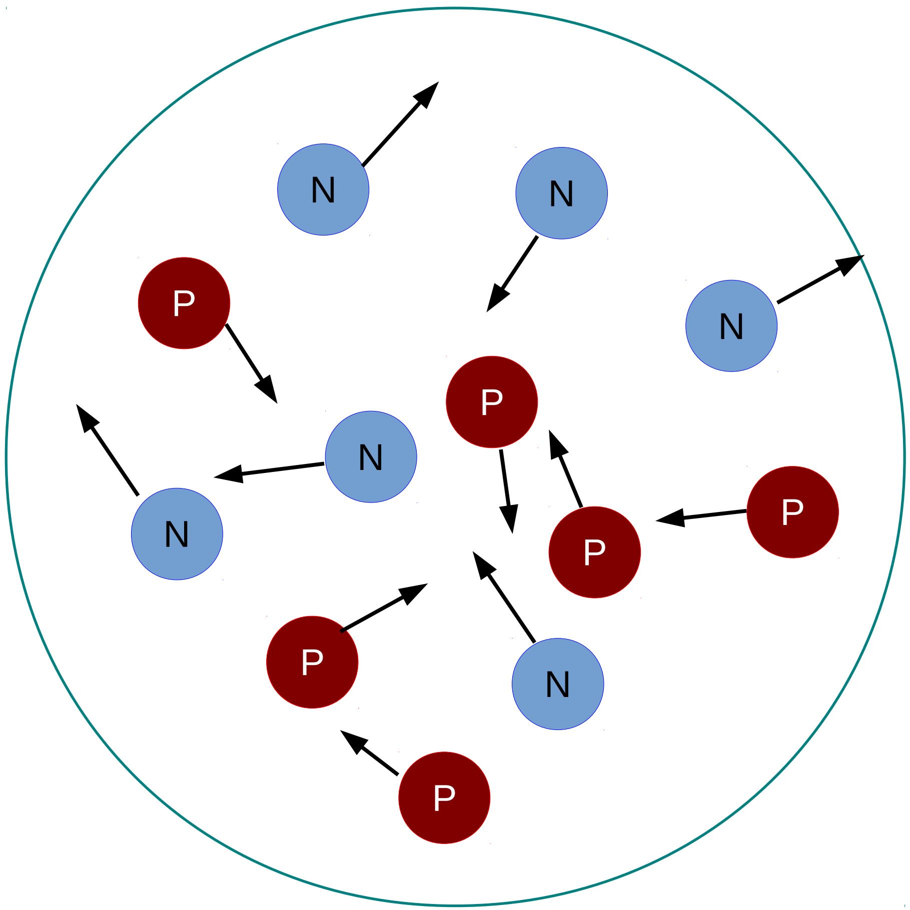
Warning:

We are now entering the ~~messy~~ *rich* realm of nuclear physics.

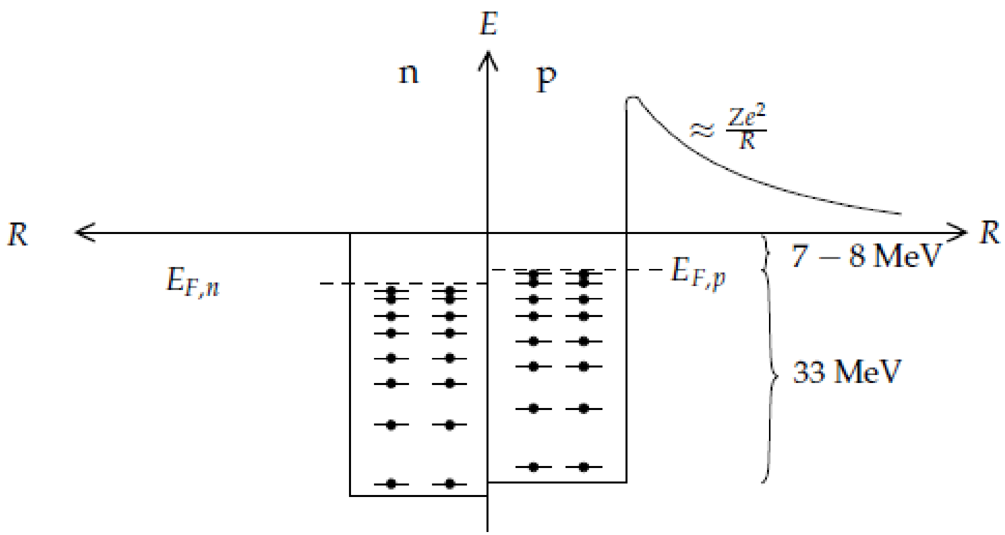
I am not a nuclear physicist
so this will be very conceptual

[hopefully I don't tell too many lies]

Modeling the nucleus



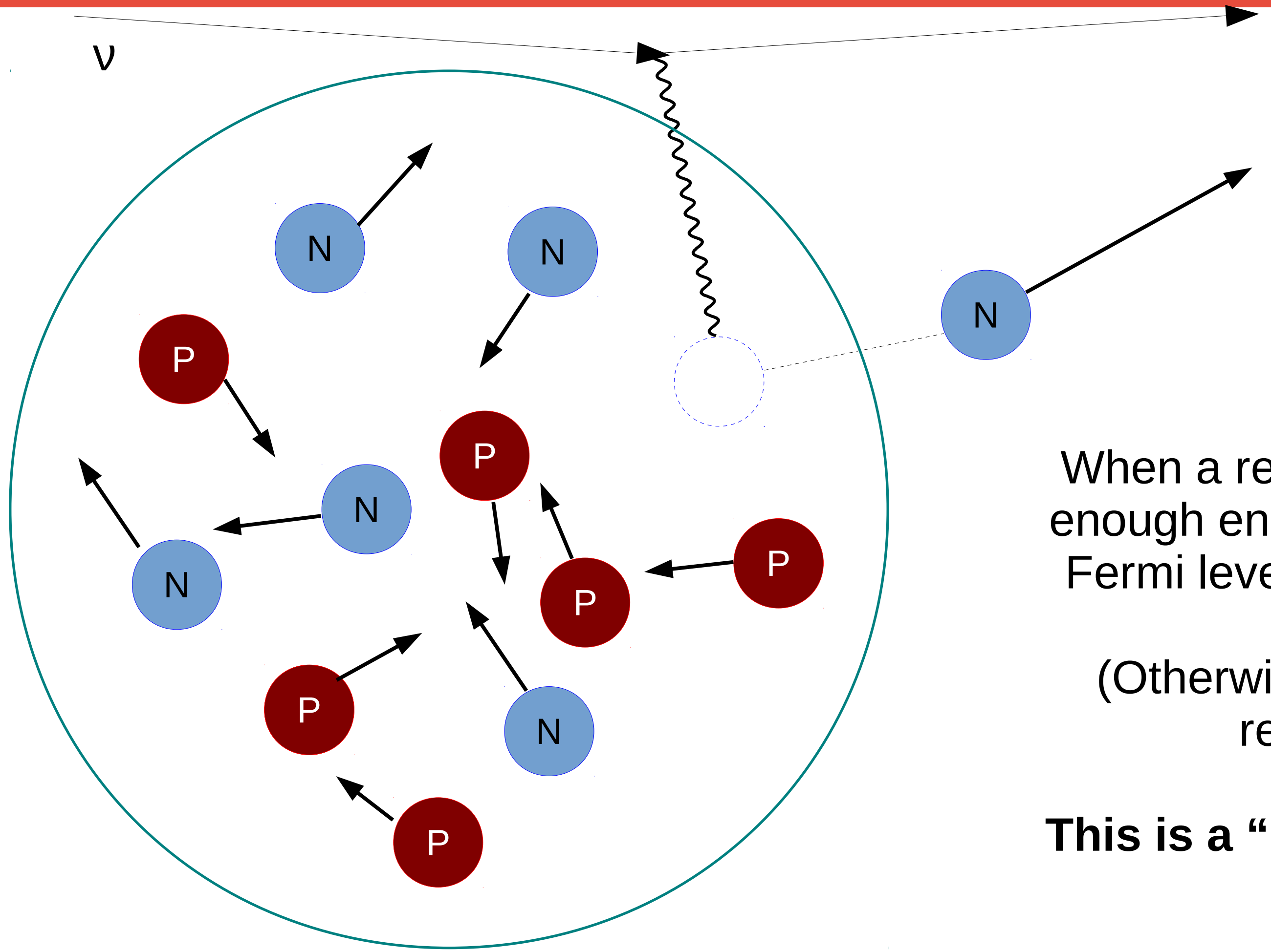
Zeroth order:
independent particle model (IPM)
“Fermi gas”



Just Dirac statistics:
Nuclear states filled up to Fermi level.
Their energy in the potential gives them
Fermi momentum.

Just like electrons in high school chemistry!

Modeling the nucleus: base model



When a reaction with a neutrino transfers enough energy to put a nucleon above the Fermi level + binding energy, it's ejected.

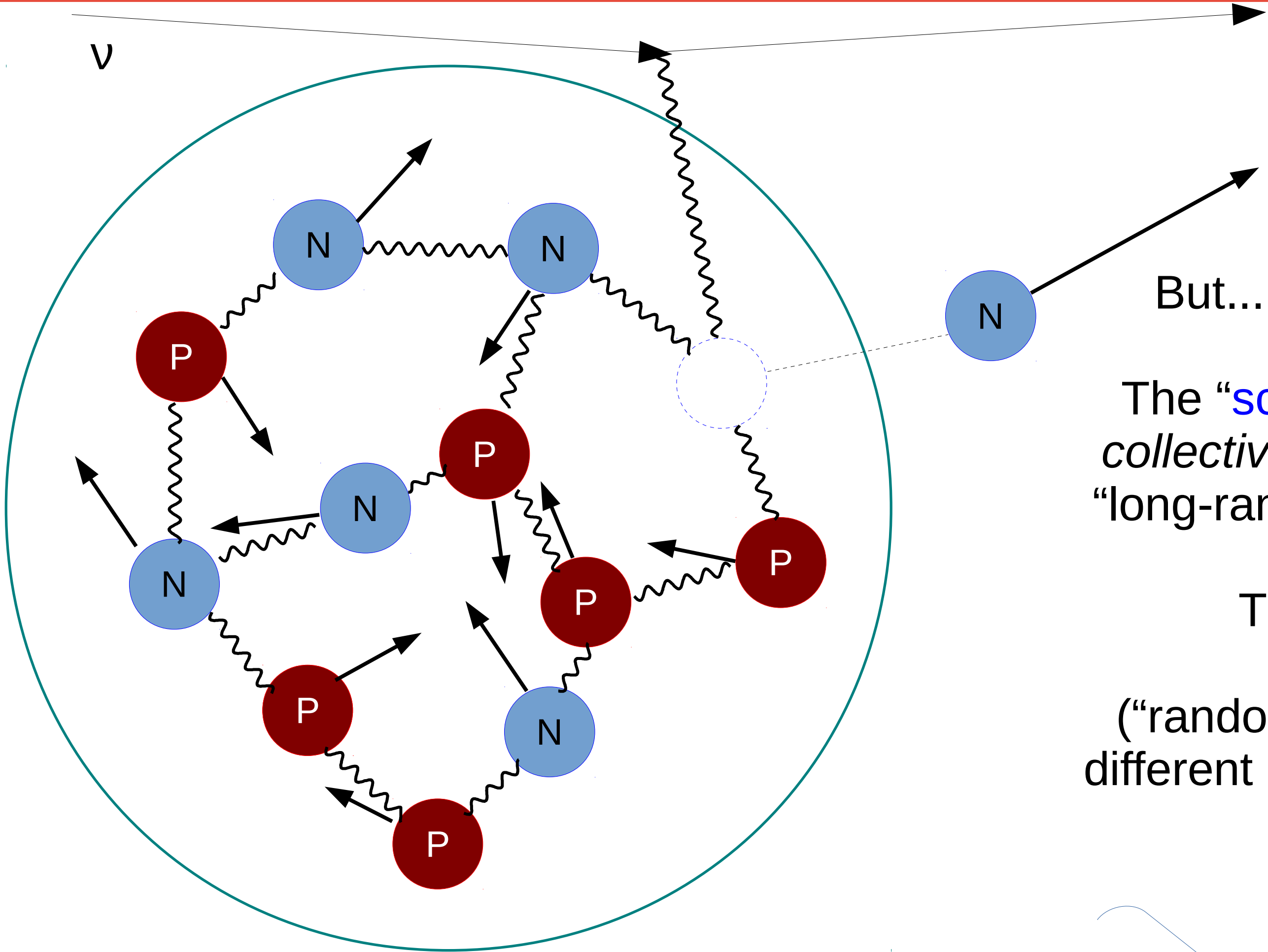
(Otherwise, it's *Pauli blocked,* and the reaction is suppressed.)

This is a "one particle, one hole" (1p1h) reaction.

→ ~GENIE's base model

Zeroth order:
independent particle model (IPM)
"Fermi gas"

Modeling the nucleus: collective effects



But... nucleons aren't non-interacting.

The “screening potential” corresponds to *collective* excitations of the whole nucleus: “long-range” interactions between nucleons

Treated with **Random Phase Approximation: RPA**
(“random phase”: collective excitations of different momenta are orthogonal → phases can be treated randomly)

First order:
Nucleon experiences

total potential = **external potential**
+ **screening potential**

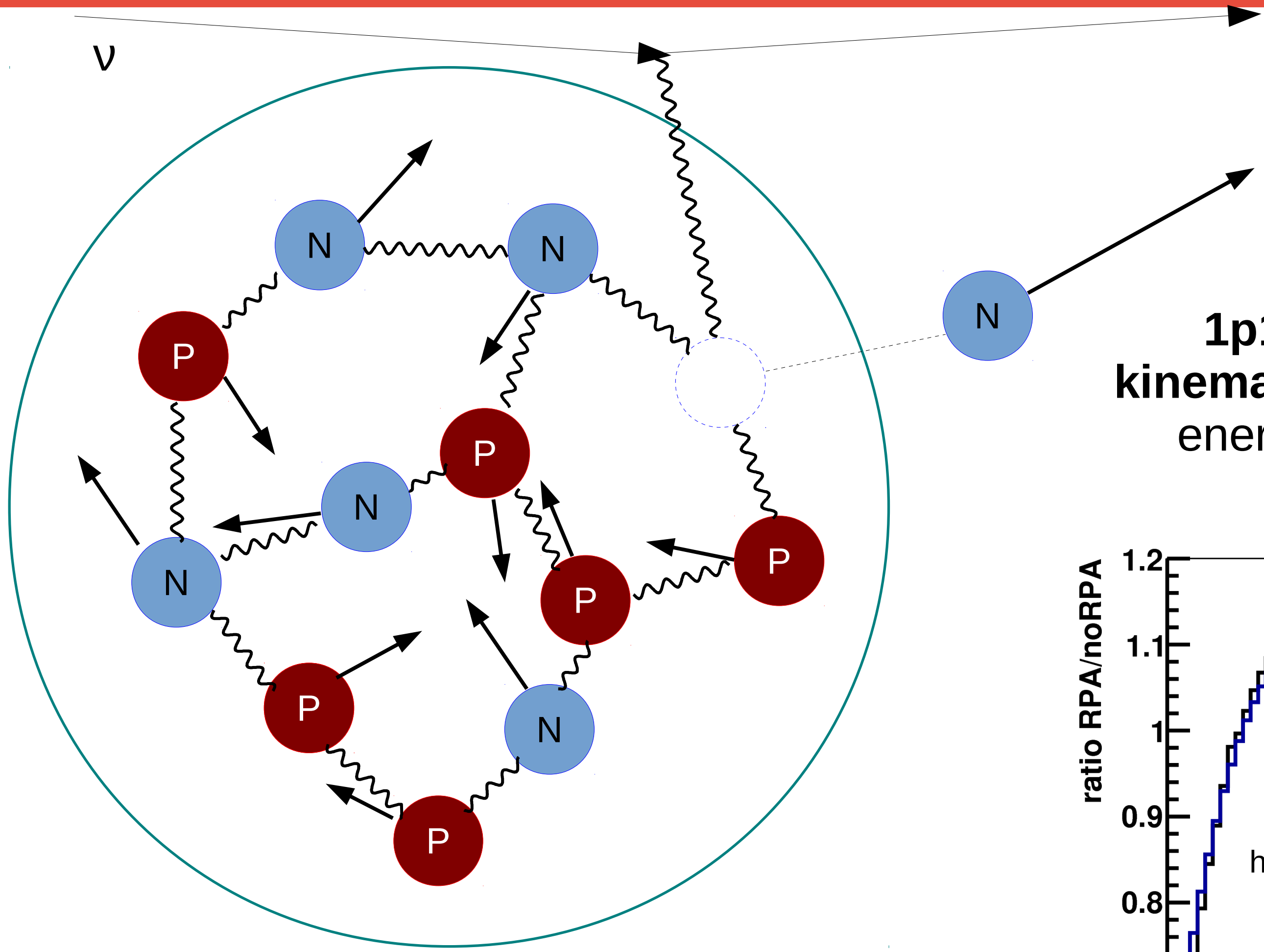
Probe field (i.e., neutrino)

Field with other nucleons

Assumed to decouple;
very different energy scales

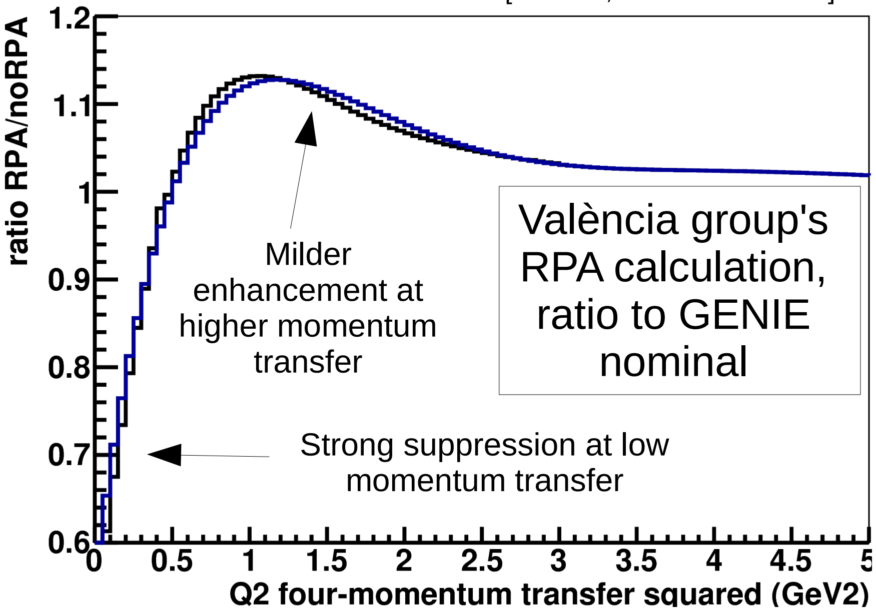
[Fun fact: RPA originally comes from treating *electrons* in matter. Wikipedia has a decent summary.]

Modeling the nucleus: collective effects



Result:
1p1h reaction is modified in a kinematics-dependent way as reaction energy is absorbed by the nucleus

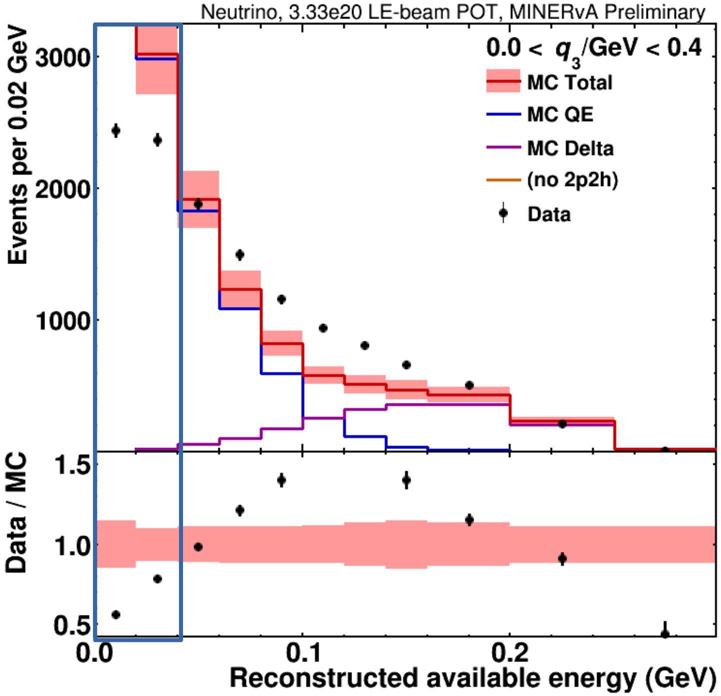
[R. Gran, arXiv:1705.02932]



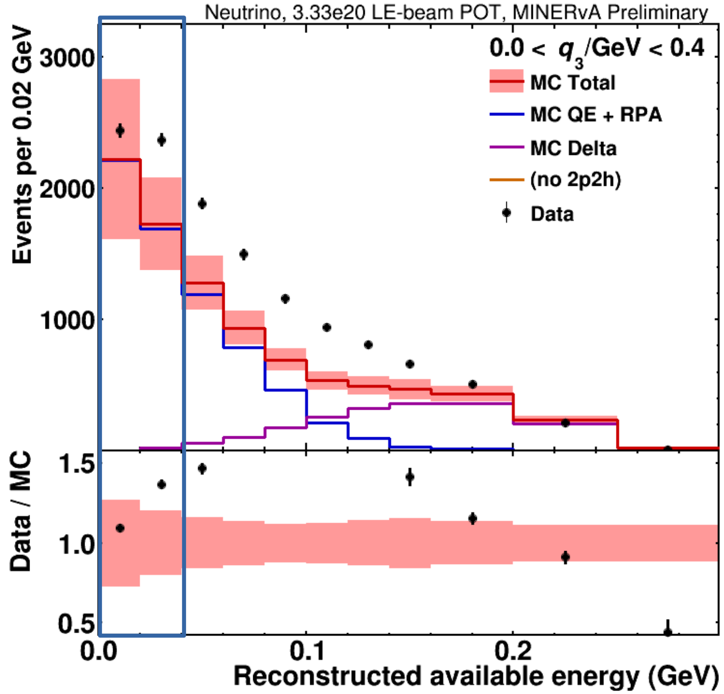
First order:
Nucleon experiences
total potential = external potential
+ screening potential

Modeling the nucleus: collective effects

[R. Gran, NuInt 2017; MINERvA, PRD 116, 071802]



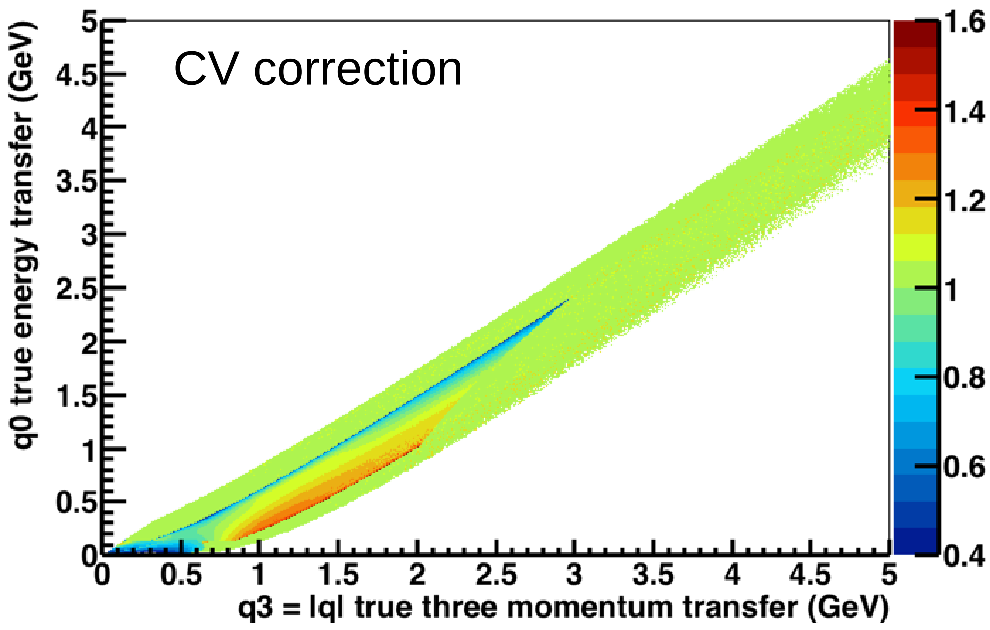
València RPA CCQE treatment



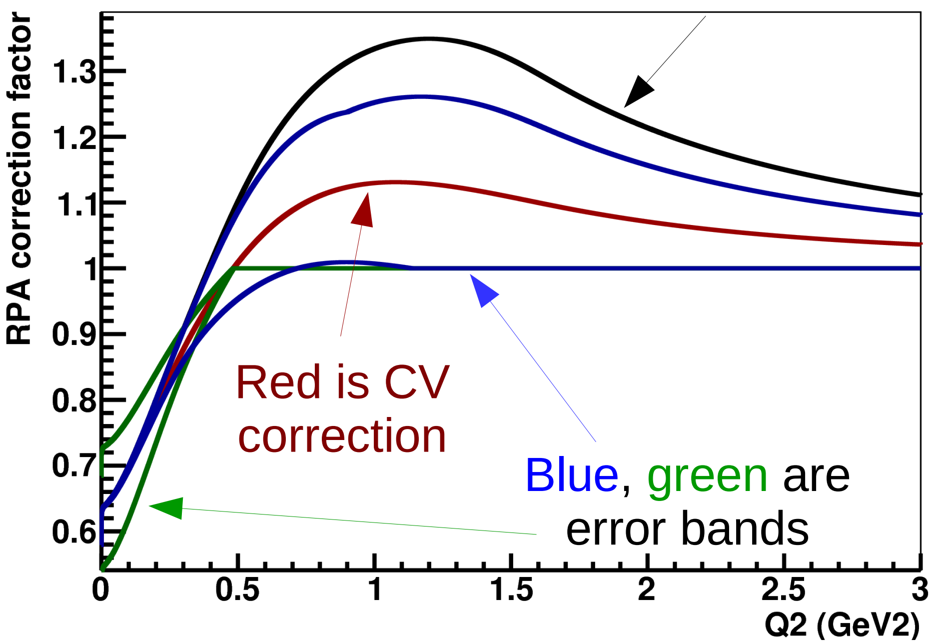
MINERvA data suggests this is an important ingredient

Modeling the nucleus: collective effects

[R. Gran, arXiv:1705.02932;]



Black is non-relativistic variant of RPA model

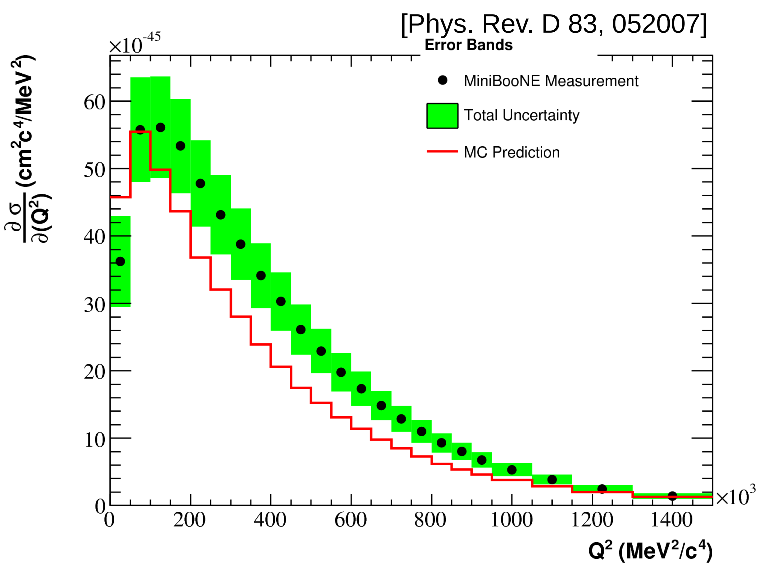


Rik Gran's work (originally for MINERvA) to extend the València RPA CCQE effect (PRC 70, 055503) to a correction for GENIE's central value and his work to extend the uncertainties in the model to higher energies (PLB 638, 325, PRD 88, 113007) naturally work reasonably well for NOvA

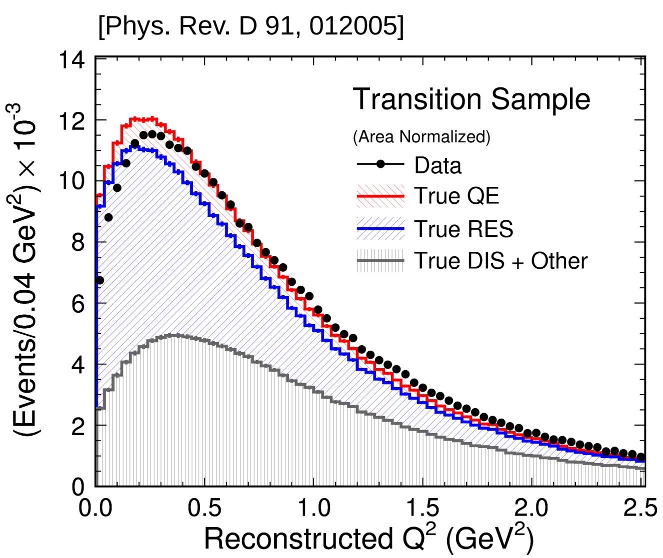
→ we apply using Rik's code

Modeling the nucleus: collective effects

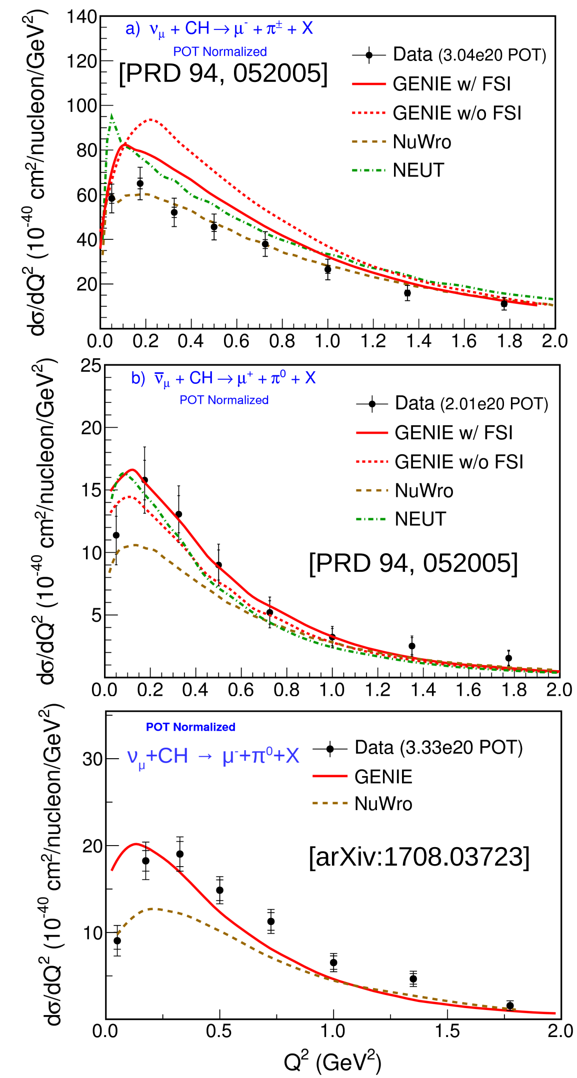
- **Should Δ production also be affected?**
  - Seems likely for same reasons as elastic.
    No current attempts at calculation?
  - Possible evidence: MiniBooNE, MINOS, MINERvA observations of apparent low-Q^2 suppression



MiniBooNE 1π+



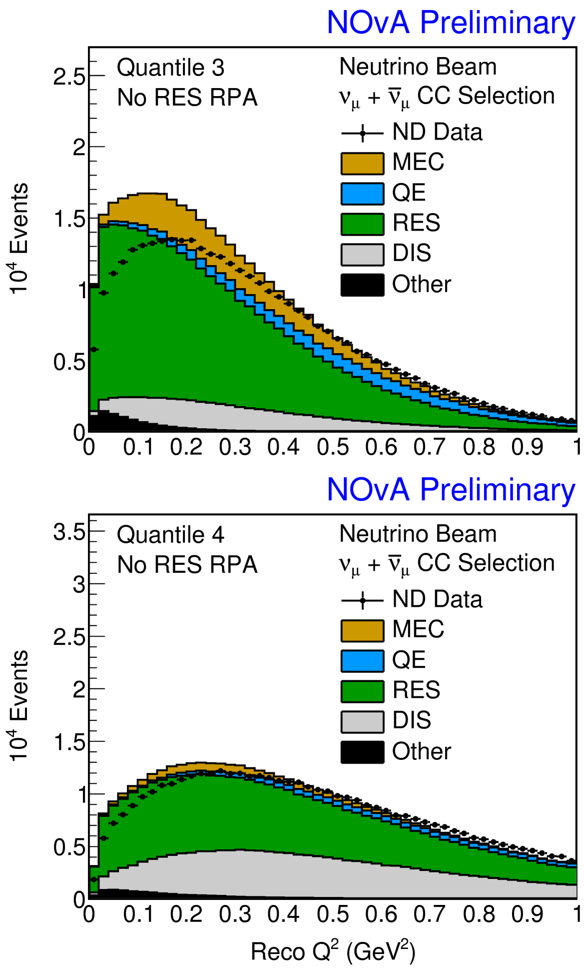
Sideband, MINOS QE



MINERvA

Modeling the nucleus: collective effects

- **Should Δ production also be affected?**
  - Seems likely for same reasons as elastic.
    No current attempts at calculation?

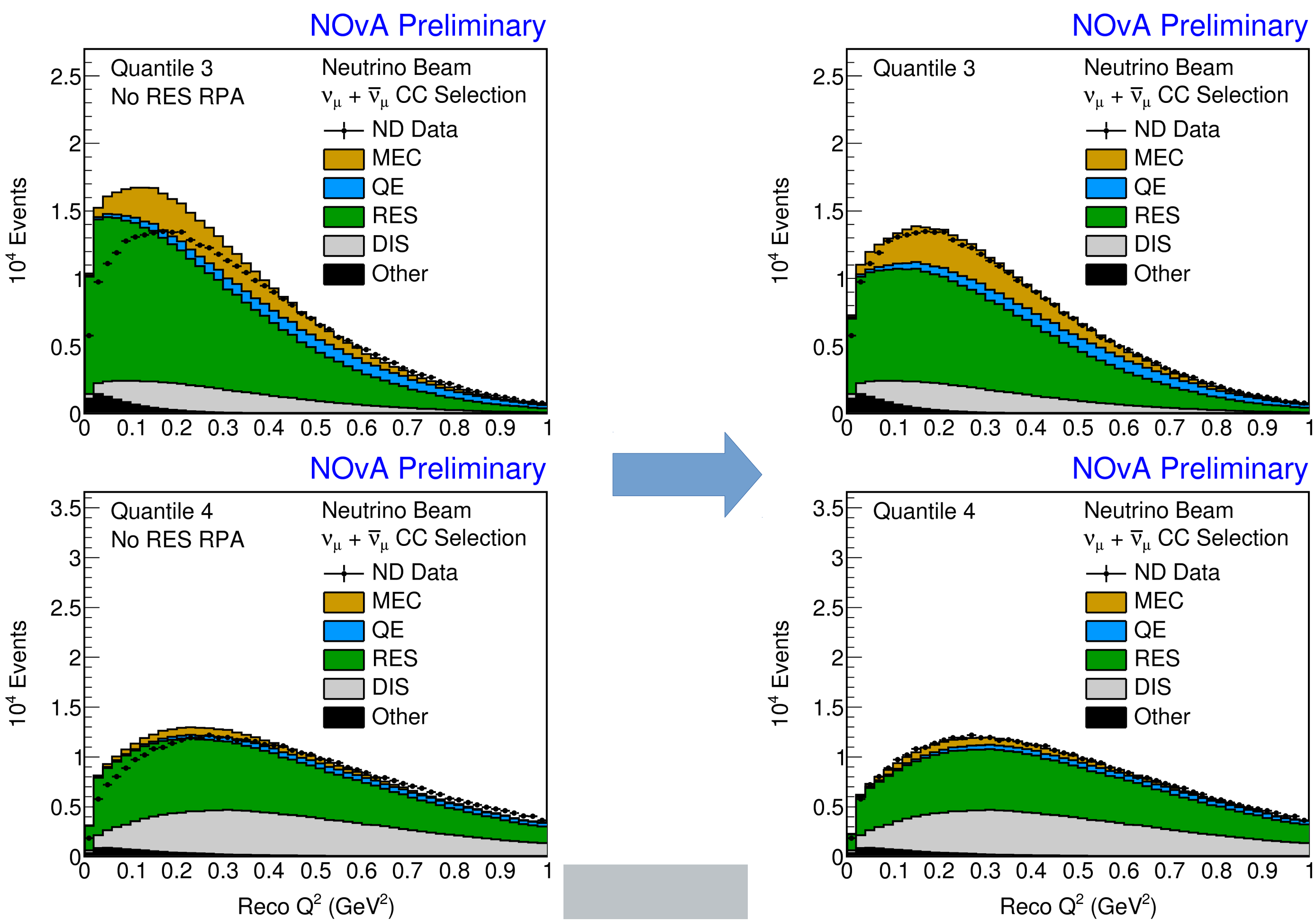


(RES-rich regions of ν_μ candidate sample)

NOvA appears to observe this as well

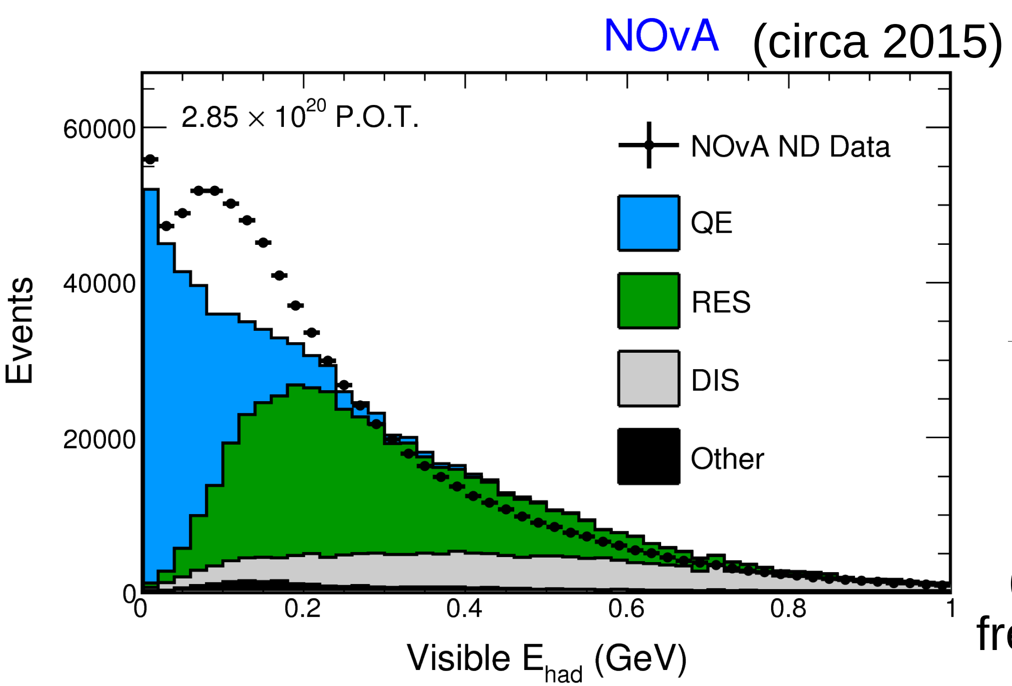
Modeling the nucleus: collective effects

- **Should Δ production also be affected?**
  - Seems likely for same reasons as elastic.
    No current attempts at calculation?

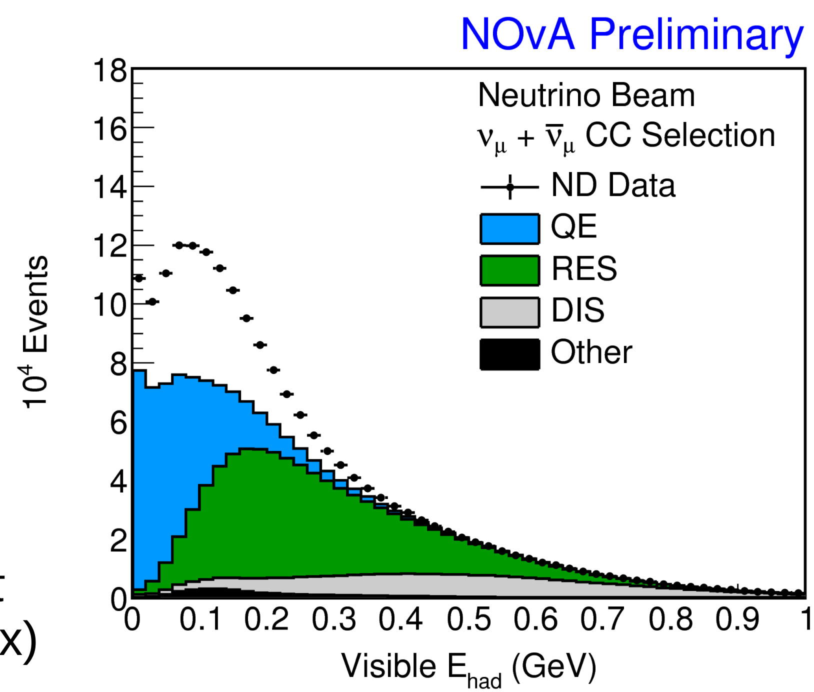


We speculatively apply the Q^2-based RPA weight from QE to resonant production as well
(w/ unmodified version as uncertainty variation)

Back to the data



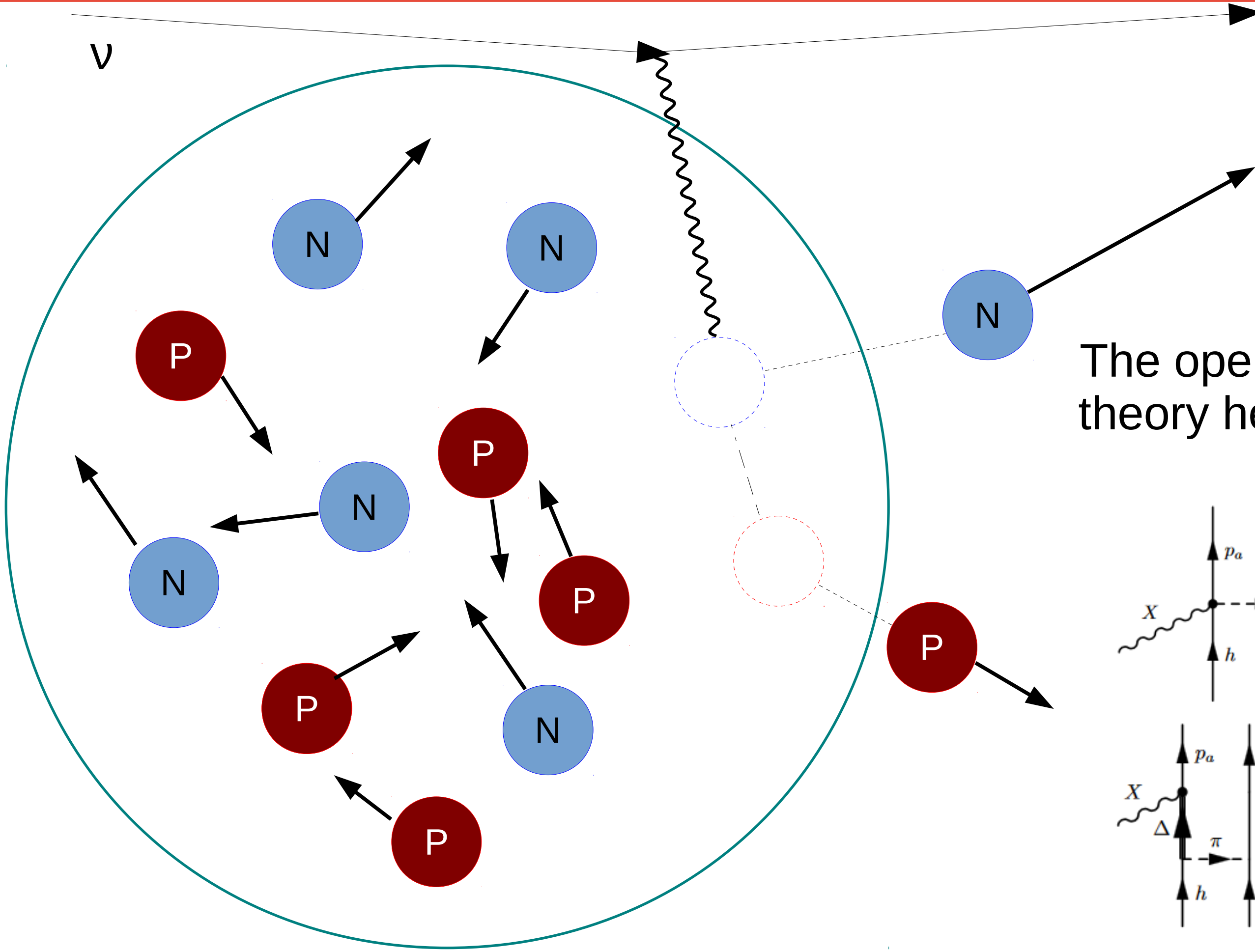
RPA-QE
+
RPA-RES
(+ nonres 1π
free nucleon fix)



Doing better in the tail, but still that gaping hole...

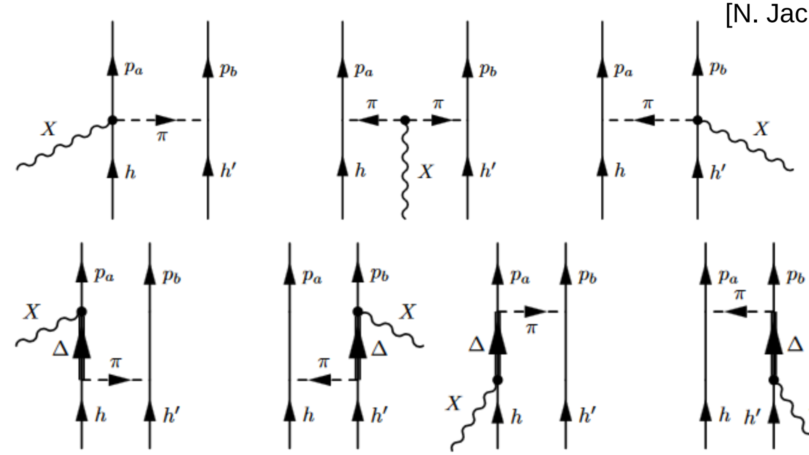
We have another layer to add, though!

Modeling the nucleus: multibody operators



The operator expansion used for the field theory here has higher-order terms which are relevant.

[N. Jachowicz]

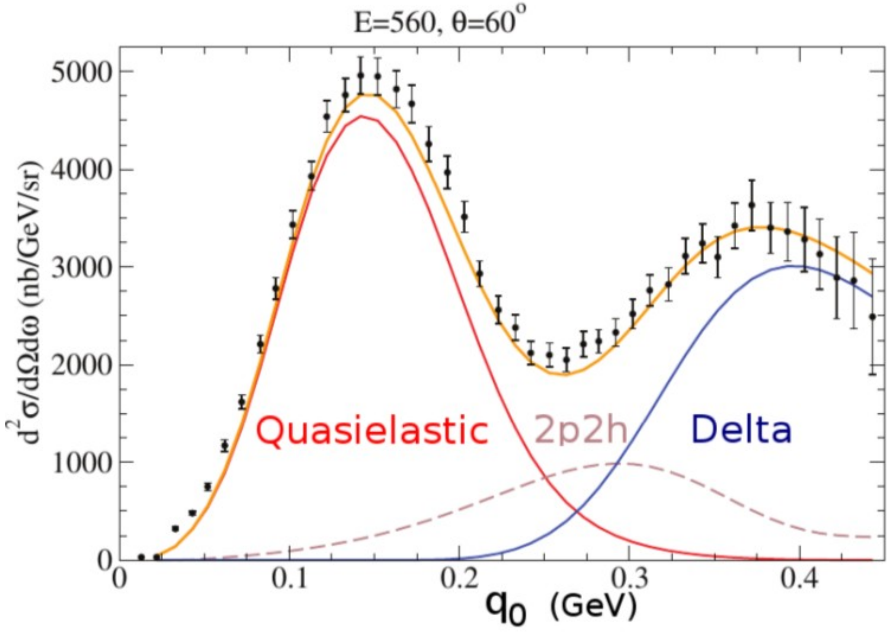


These "two particle, two hole" (2p2h) reactions via **meson exchange currents** (MEC) are non-negligible in accelerator neutrino interactions

First order:
Two-body operators
(even in Fermi gas!)

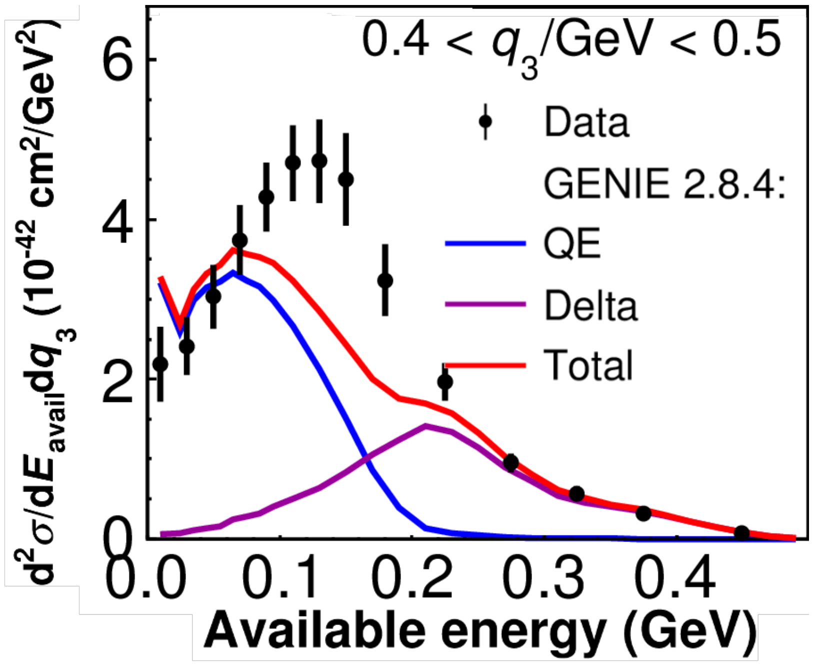
Modeling the nucleus: multibody operators

Adapted from G. D. Megias, NuFact 2015



First discovered in electron scattering in the 80s

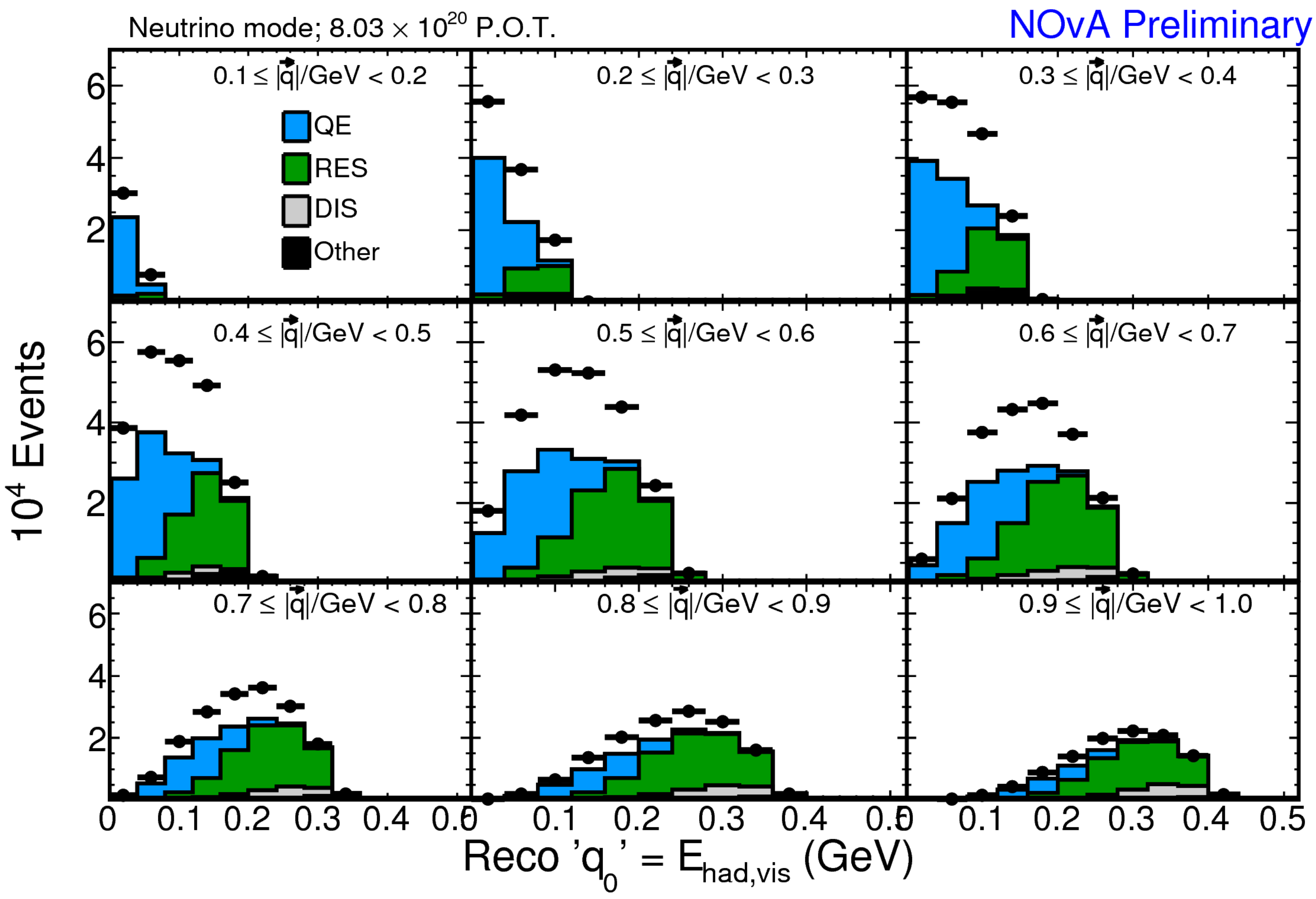
Adapted from P. Rodrigues, FNAL JETP, Dec. 11 2015; MINERvA, PRD 116, 071802



Same phenomenon apparently observed in MINERvA neutrino data in last few years

The manifestation is reactions with two nucleons in the final state, with energy transfer *between* elastic and resonant production.

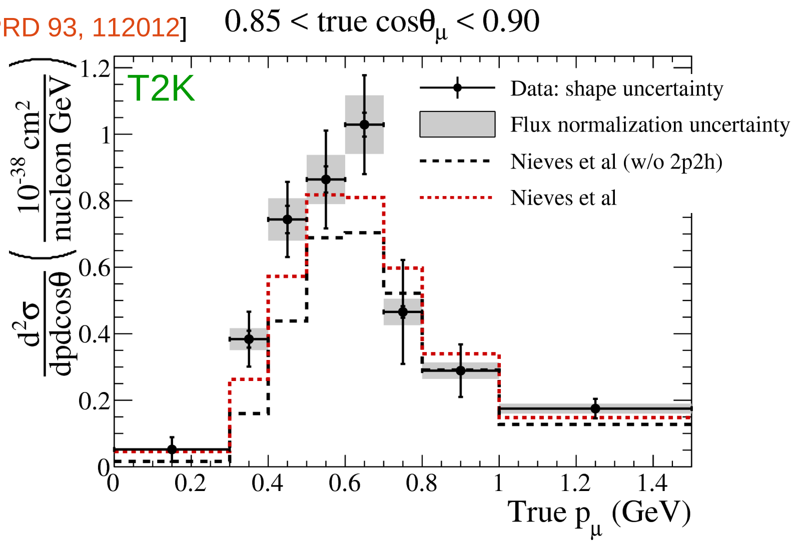
Modeling the nucleus: multibody operators



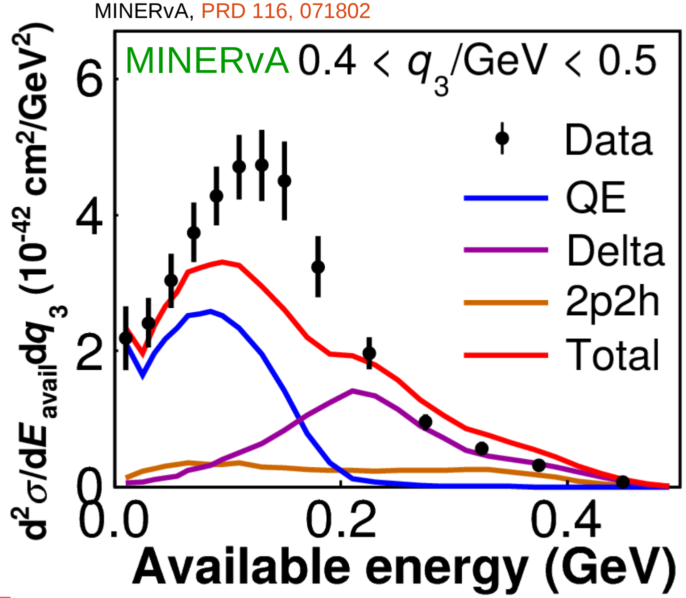
Our data excess (relative to the model with the previous modifications) behaves the same way as the predictions from MEC-based 2p2h models.

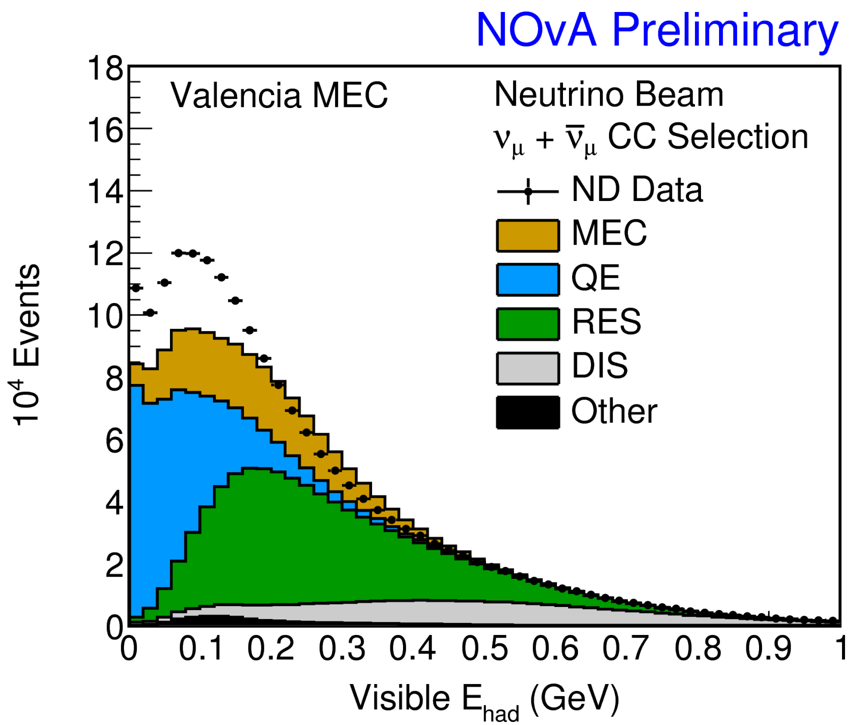
Modeling the nucleus: multibody operators

[PRD 93, 112012]



Adapted from P. Rodrigues, FNAL JETP, Dec. 11 2015;
MINERvA, PRD 116, 071802





The only real theoretical MEC model available in GENIE (from the València group again, PRC 70, 055503) doesn't describe any recent data very well.

→ Forced to do something empirical.

Modeling the nucleus: multibody operators

We begin with GENIE's "Empirical MEC"
model to supply MEC events

(None of the others provide *neutral-current* MEC,
which is potentially important for our sterile neutrino searches.
Plus we're heavily tuning the kinematics to our data,
so the differences between the models are not very important.)

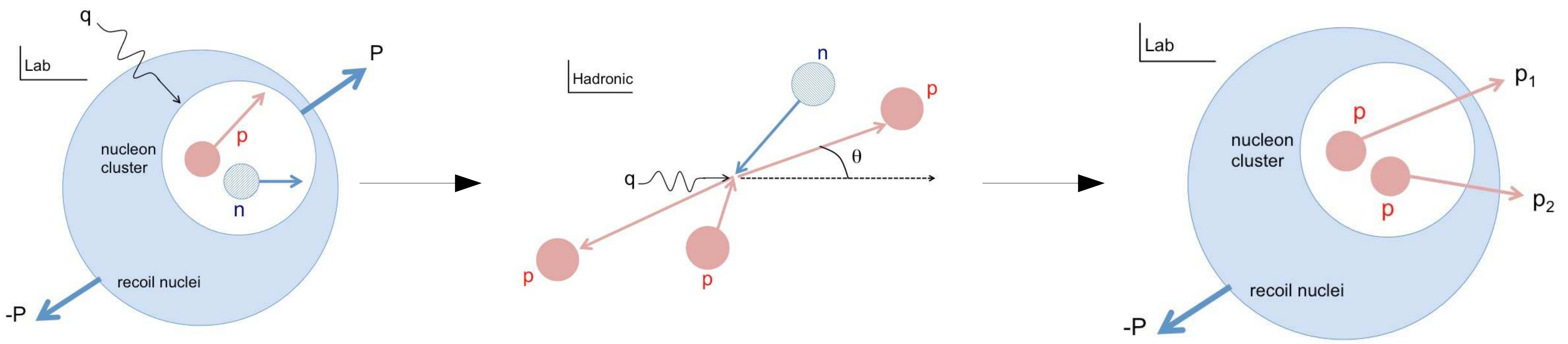
Modeling the nucleus: multibody operators

We begin with GENIE's "Empirical MEC"
model to supply MEC events:

Leptonic system treatment:

Original model uses transverse (Sachs magnetic) form factor, inspired by electron scattering observations. → We tune this to data. Initial model not that important

Hadronic system treatment:



[T. Katori, AIP Conf. Proc. 1663, 030001]

4-momentum delivered to "clustered" nucleon pair, which then "decays" isotropically in COM frame

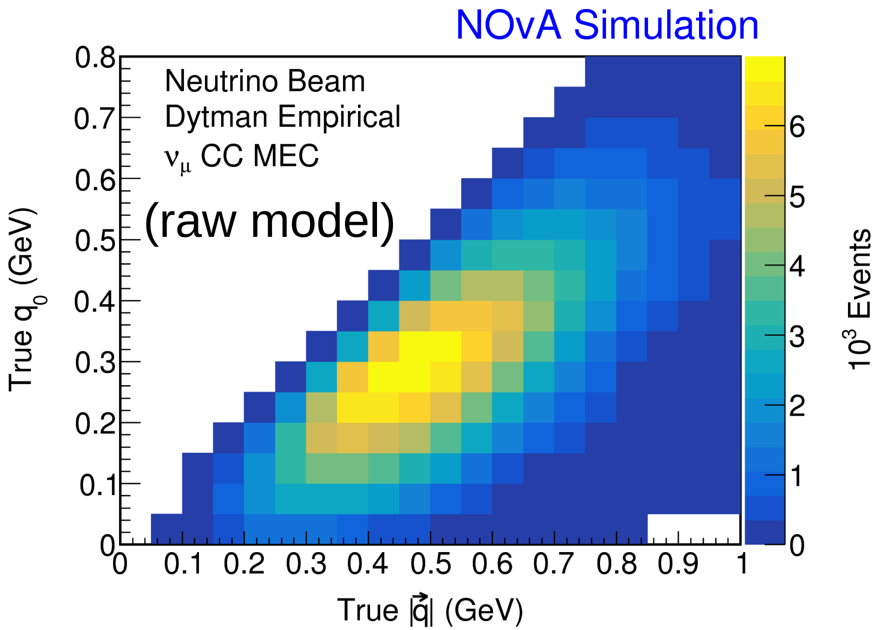
Modeling the nucleus: tuning 2p2h-MEC

Our tuning is done in a two-dimensional space of the four-momentum transfer variables:

energy transfer q_0

and

momentum transfer |q|



fit a weight factor for each cell in this plot

We fit our MC to ν_μ CC data distributions in the closest observables:

Visible non-muon energy (~q_0)

(uncorrected for neutrals)

and

reconstructed momentum transfer (~|q|)

where

$$q_0 = E_{had}$$

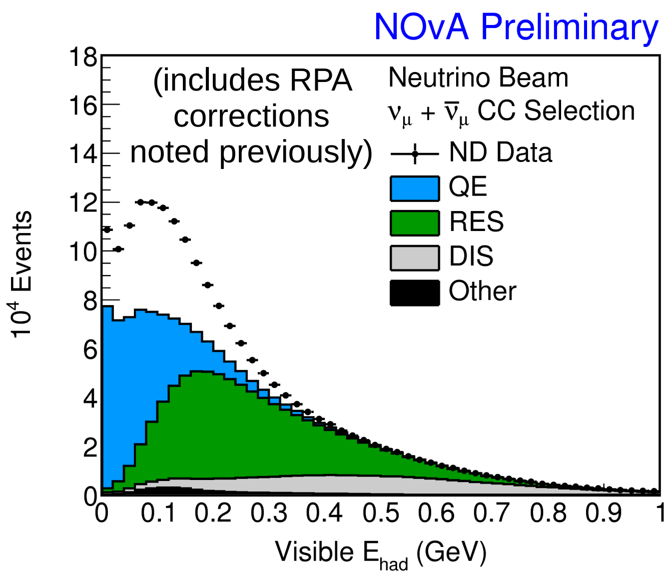
calibrated to true q_0 by MC, unlike above

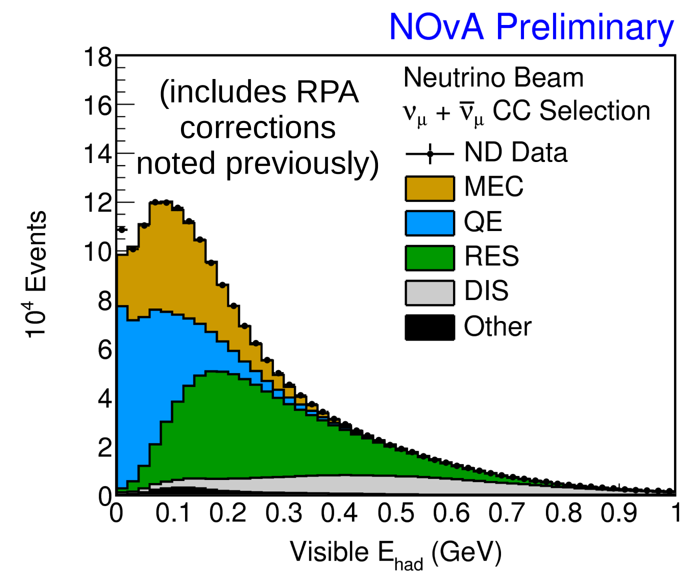
$$E_\nu = E_\mu + E_{had}$$

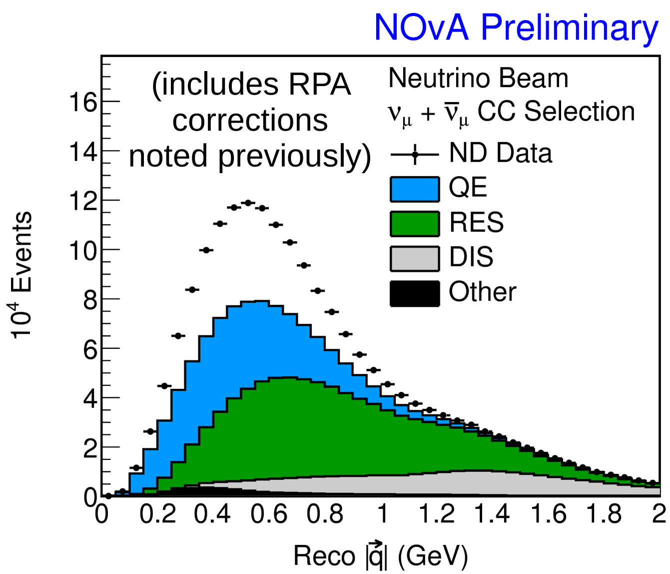
$$Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_\mu - M_\mu^2\right)$$

$$|\vec{q}|^2 = Q^2 + q_0^2$$

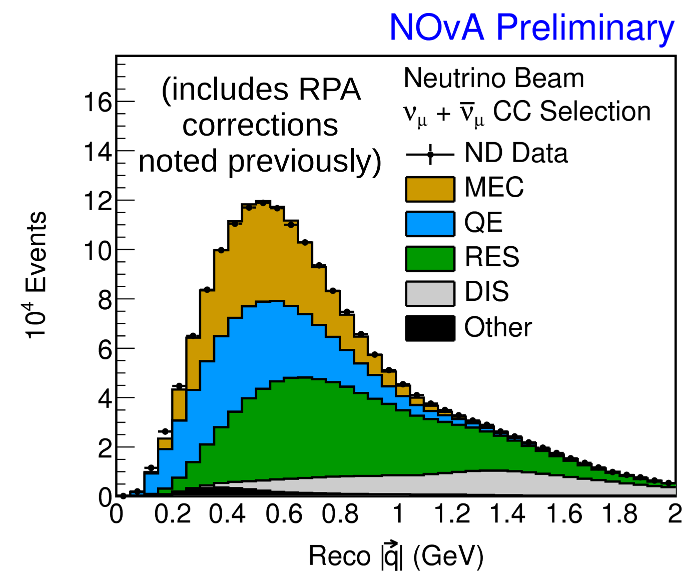
Modeling the nucleus: tuning 2p2h-MEC



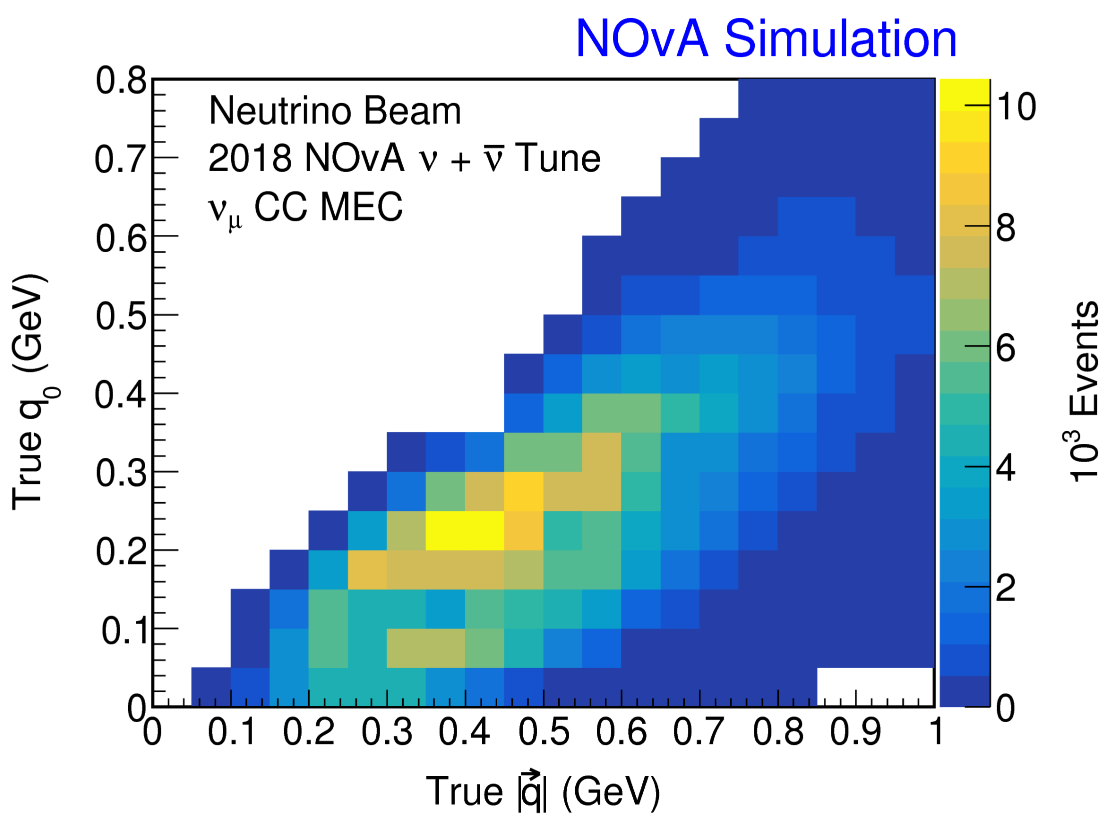




We are able to obtain pretty good agreement via this procedure

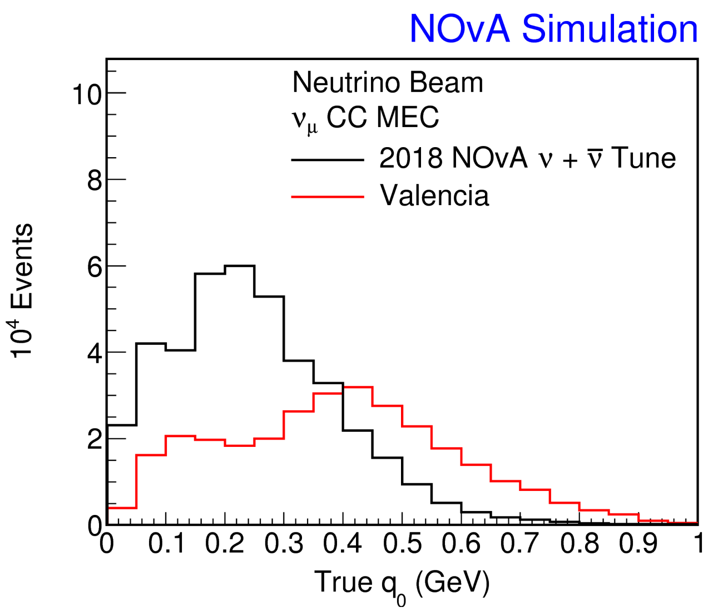


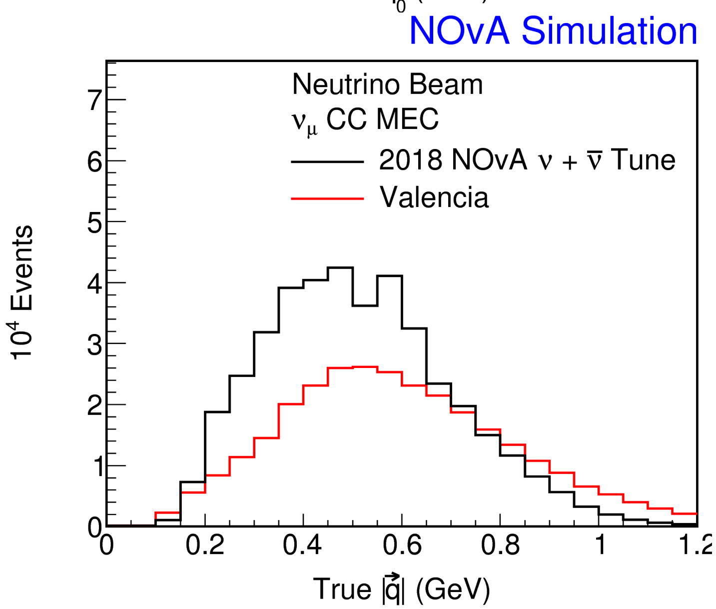
Modeling the nucleus: tuning 2p2h-MEC



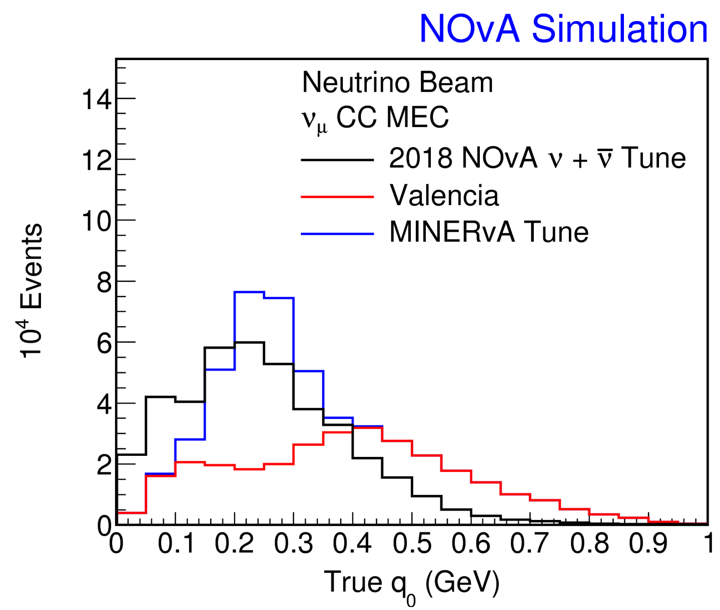
Resulting distribution is intriguingly bimodal...

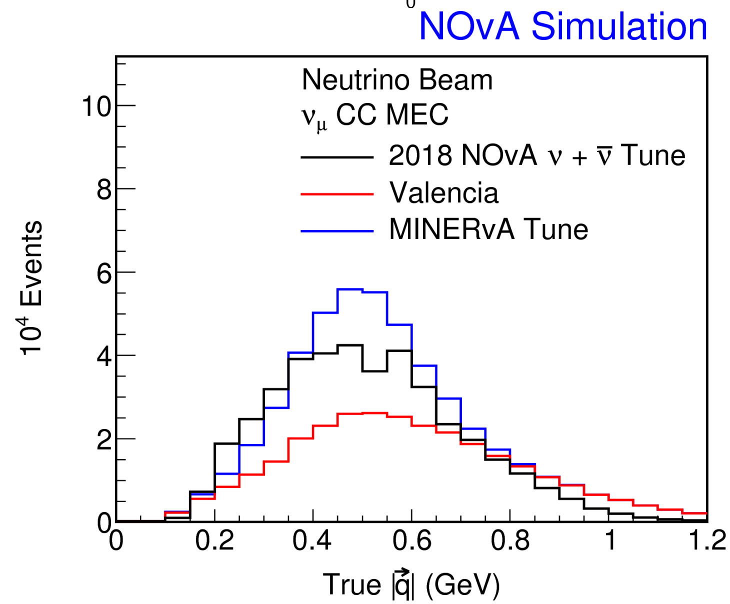
(reminds one of the delta-like and non-delta-like parts of Valencia model, though different phase space)





Modeling the nucleus: tuning 2p2h-MEC





MINERvA carried out a tuning procedure similar in spirit to ours (though with fewer degrees of freedom) using their data (PRD 116, 071802) which they kindly shared with us (private communication).

Our result is not wildly different from theirs, but we do see a stronger component at lower energy transfer.

Modeling the nucleus: 2p2h-MEC uncertainties

- **This tuning procedure makes several assumptions:**
  - The steps are orthogonal and sequential:
    fix single nucleon XSs → apply RPA to QE,RES → tune MEC
  - MEC is a suitable stand-in for everything that's missing in the region intermediate between QE and RES in q_0. *Seems plausible based on e-scattering?*
- **Assuming we can fill the gap in with MEC... what is uncertain?**
  - Four-momentum transfer response
    Try refitting under different initial assumptions. (Possibly over-conservative; nuisance parameter + covariance method explored in future?)
  - Neutrino energy dependence of the cross section (don't want Empirical MEC's!)
    Models disagree. Hard to infer from measurements. Use "model spread"
  - Fraction of 2p2h events resulting in pp final-state pairs vs np pairs
    Different answers from different models. Weak constraint from current measurements. Use "model spread"

Let's discuss these...

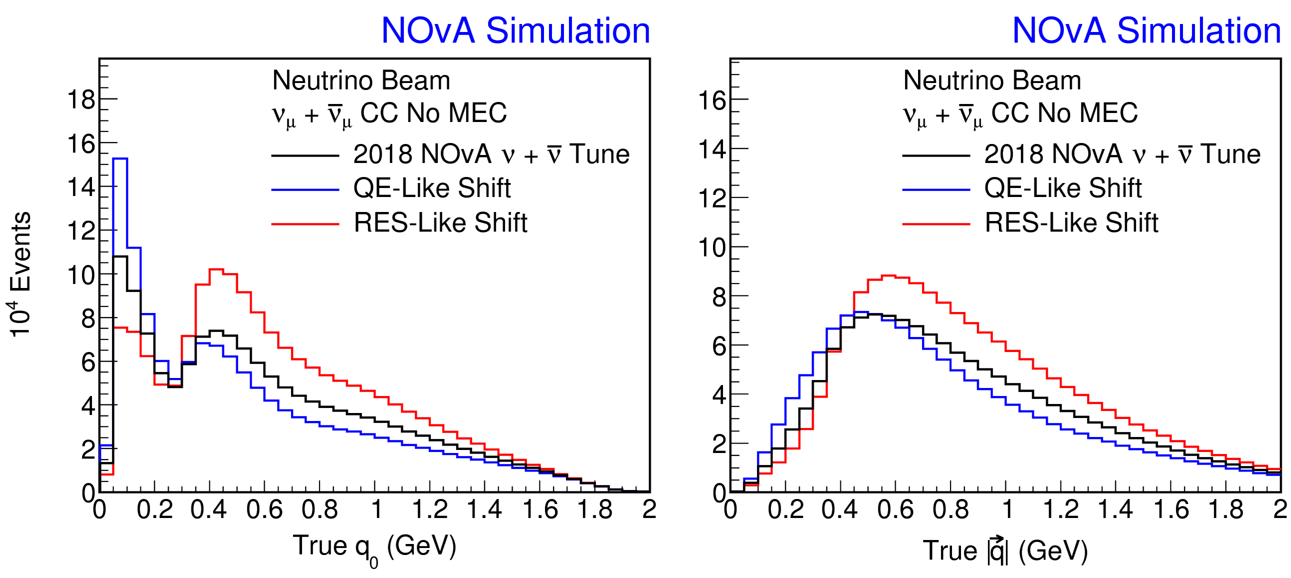
Modeling the nucleus: 2p2h-MEC uncertainties

Momentum transfer shape

Two alternate fits:

Choose combinations of uncertainties to push initial MC more towards QE or RES

Knob	"QE-like" shift	"RES-like" shift
QE MA	+1σ (+5%)	-1σ (-5%)
QE RPA low-Q^2	+1σ	-1σ
QE RPA high-Q^2	+1σ	-1σ
QE Pauli Supp.	-1σ	+1σ
RES MA	-1σ	+1σ
RES MV	-1σ	+1σ
RES RPA	on (CV)	off



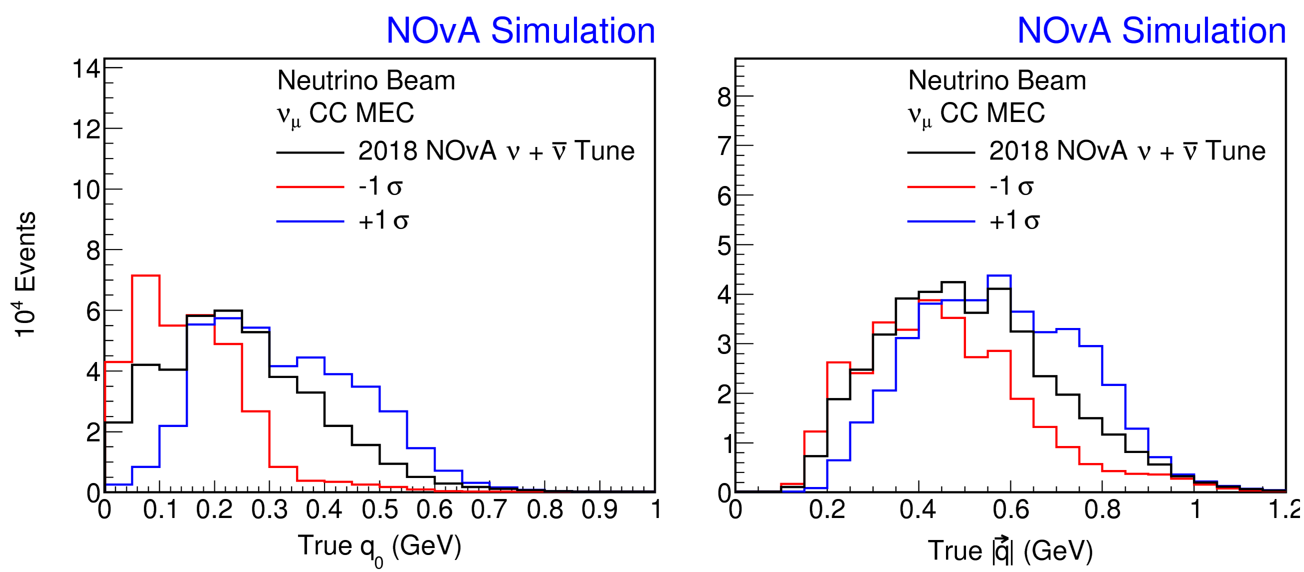
Modeling the nucleus: 2p2h-MEC uncertainties

Momentum transfer shape

Two alternate fits:

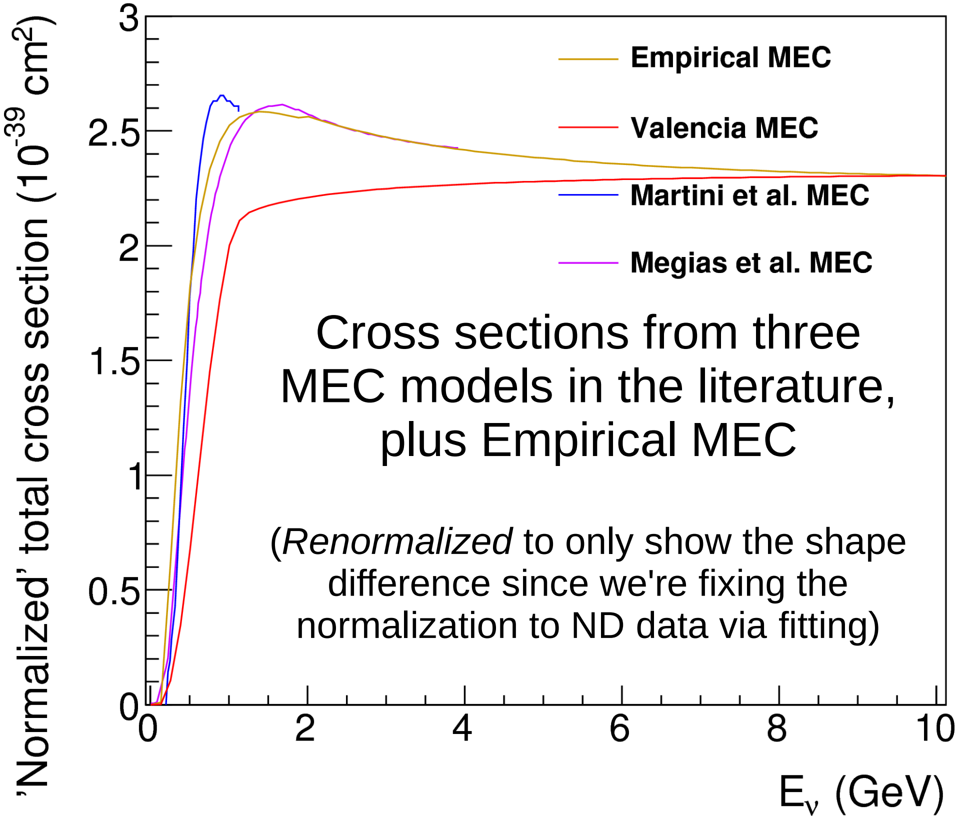
Choose combinations of uncertainties to push initial MC more towards QE or RES

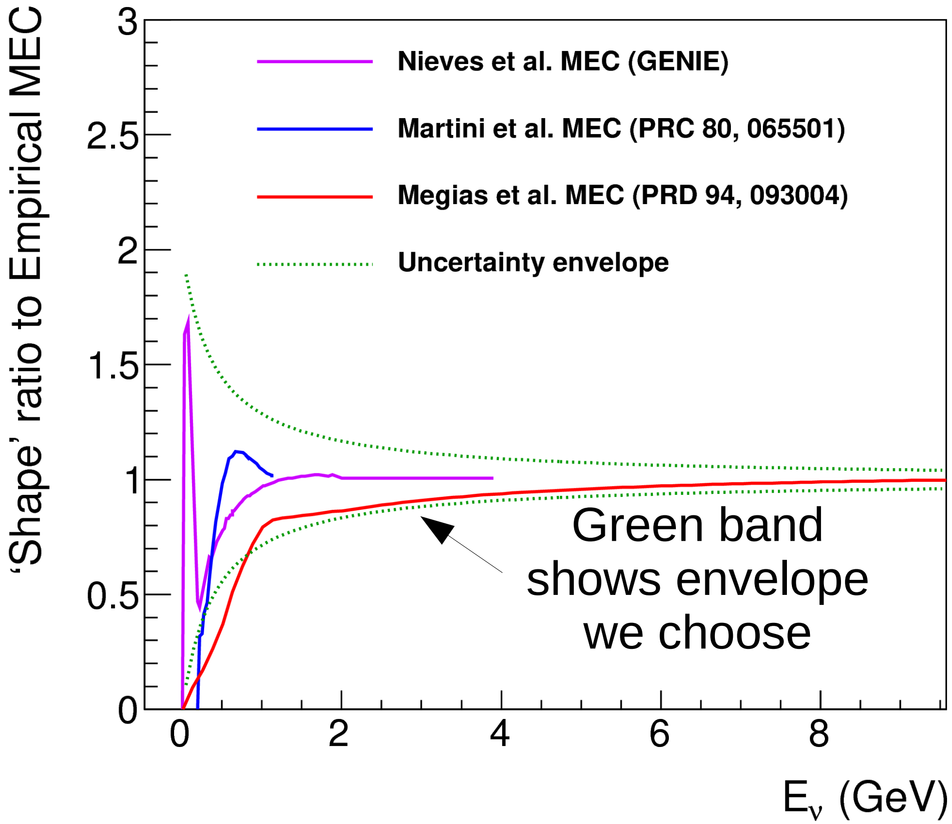
Knob	"QE-like" shift	"RES-like" shift
QE MA	+1σ (+5%)	-1σ (-5%)
QE RPA low-Q^2	+1σ	-1σ
QE RPA high-Q^2	+1σ	-1σ
QE Pauli Supp.	-1σ	+1σ
RES MA	-1σ	+1σ
RES MV	-1σ	+1σ
RES RPA	on (CV)	off



Modeling the nucleus: 2p2h-MEC uncertainties

Cross section E_ν shape



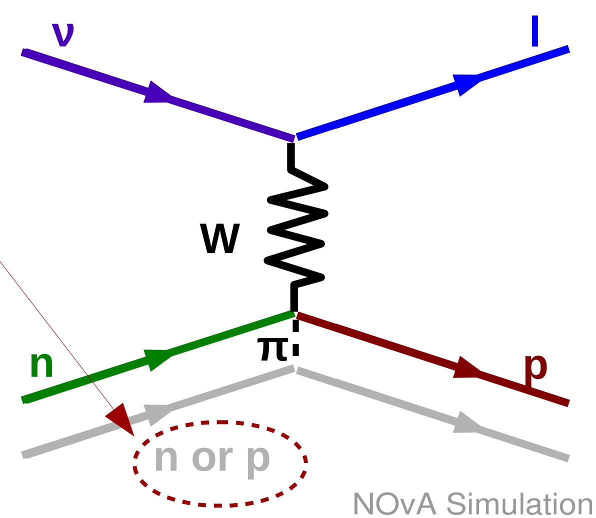


Choose an envelope that more or less encloses the shapes of the predictions for our "±1σ" uncertainty

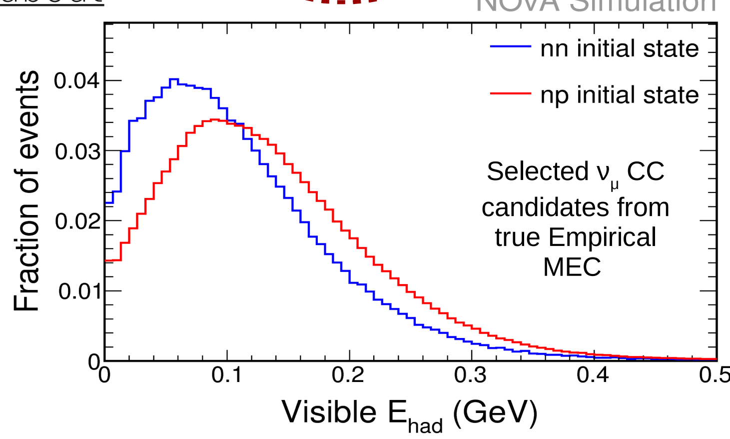
Modeling the nucleus: 2p2h-MEC uncertainties

nn-np initial state composition

- **Diagrams for ν CC 2p2h allow two nucleon "pairs" in initial state: nn or np ($\bar{\nu}$ has np or pp)**
- **Challenging to measure the real composition in data**
  - LAr will help eventually?
  - MINERvA has made valiant efforts in the meantime, but not strong constraints on the ***value*** of the ratio (yet?)
- **Stuck with theory for now**
  - València prediction (via GENIE): ~70% np/(nn+np).
  - SuSA prediction (PRC 94, 054610), detailed study: "The [np/nn] ratio is about 5-6 [i.e., np/(nn+np) ~ 80-90%] for a wide range of neutrino energies."
  - Empirical MEC default is 80%



We choose $0.7 \le \frac{np}{(np+nn)} \le 0.9$ at 1σ.

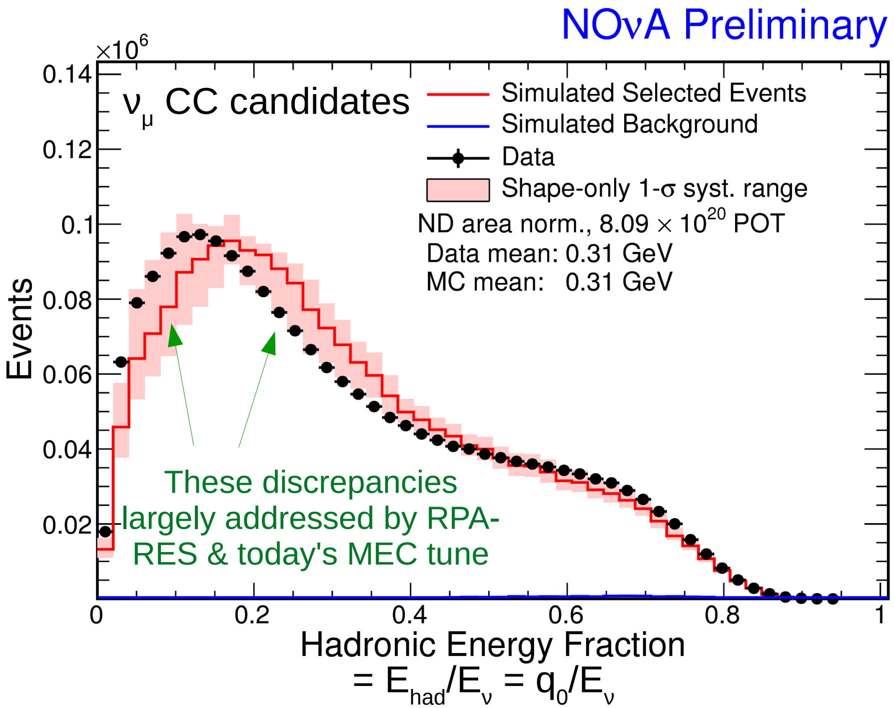


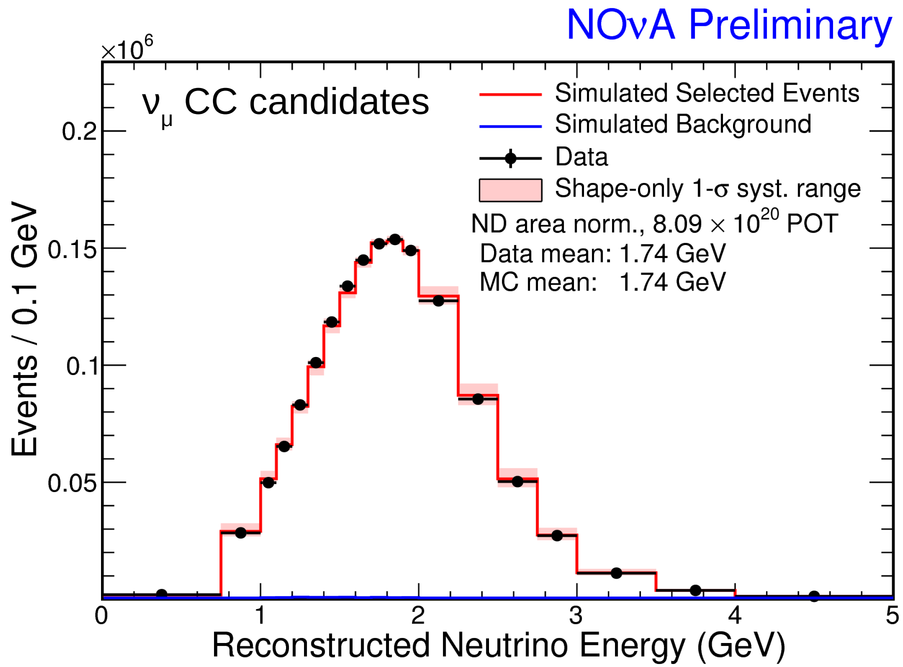
(It doesn't matter much; GEANT says we get ~similar response)

Taking stock of where we are

In our previous analysis:

[A. Radovic FNAL JETP Jan. 2018]





[full systematics for current $\nu + \bar{\nu}$ analysis not done yet, so can't show yet, but coming this summer!]

Neutrino cross sections are a hard problem, but we're making some progress!

The future

- **Model development continues**
  - GENIE 3.0, with updated tunes & uncertainties, around the corner
  - New models under consideration/in the works for later versions
    - Better nuclear physics for elastic
    - Other approaches to multibody processes like MEC

    Dedicated models for handling inelastic continuum interferences (e.g., M. Kabirnezhad)
- **NOvA cross section measurements coming soon**
  - Nobody can measure reactions with our combination of energies & target like we can…
- **We continue to digest & apply new ideas & measurements from elsewhere in the community**
  - Approaches to potential ν_e/ν_μ differences
  - Better variables for better disentangling nuclear effects we see
  - etc.

Summary

- **Modeling neutrino cross section physics needed for oscillation expts is challenging**
  - "Simple" free nucleon parameters need to be explicitly measured, and data is sparse
  - Complex nuclear physics unavoidable when using massive targets
  - Creating a self-consistent model can be extremely challenging!
- **NOvA, like others, does the best we can with what's available:**
  - Use two similar detectors to reduce exposure to uncertainties
  - Modify model *post hoc* when necessary to account for effects not included in base model
  - Treat phenomena empirically with data when no other suitable option available
  - **We are making real progress despite these challenges!**
- **We look forward to continuing the discussion & integrating advancements in theory and measurement into our results!**

Overflow

The full tune

- **The ingredients to our current full tune:**
  - **2p2h/MEC** (per preceding): CV + uncertainties
  - **RPA** (per preceding)
    - 2D (q_0,|**q**|) for CCQE: CV + uncertainties
    - 1D Q^2 for RES: CV; uncertainty = disabling RPA-RES
  - **CCQE**: set $M_A = 1.04 \pm 0.05$ based on error-weighted mean of updated ANL, BNL, FNAL expts in PRD 93, 113015
  - **Nonresonant continuum 1π production**: reduction of CV per EPJ C76, 474 (Rodrigues *et al.*)
  - **DIS 3^+-π, high-y** for transition DIS (1.4 < W/GeV < 2):
    - Default GENIE: no uncertainty
    - We force 50% uncertainty (like continuum 1,2π)
    - We increase 10% to rectify discrepancy

Modeling the nucleus: other topics

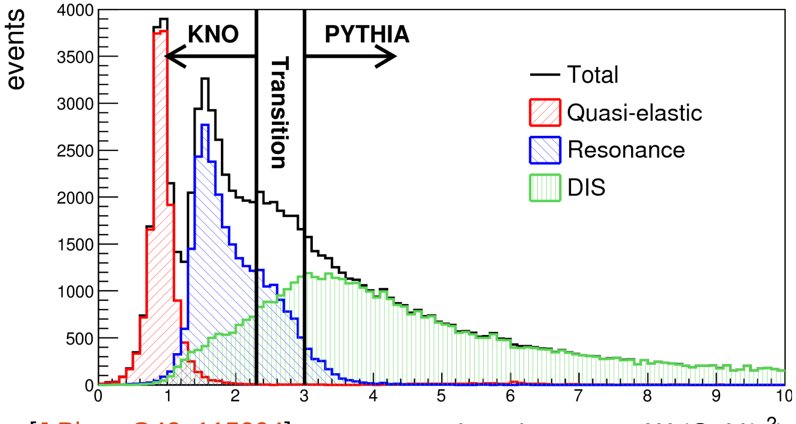
- **There are lots of important nuclear physics topics I haven't had time for today!**
  - 2p2h beyond elastic – 2p2h resonant production?
  - How might ν_μ and ν_e cross sections differ in a nuclear environment?
  - Final-state interactions – GENIE has several different model options, NOvA hasn't explored much yet (though we unc. knobs for default model in analysis)
  - Influence of nuclear environment on parton-level reactions (shadowing/anti-shadowing/EMC effect) – less important for NOvA, but relevant for heavy targets at higher E_ν (DUNE!)
  - Diffractive meson production (esp. on nuclear targets → coherent)
  - Different approaches that don't factorize free nucleon & nuclear cross sections

→ These should stay in the discussion!

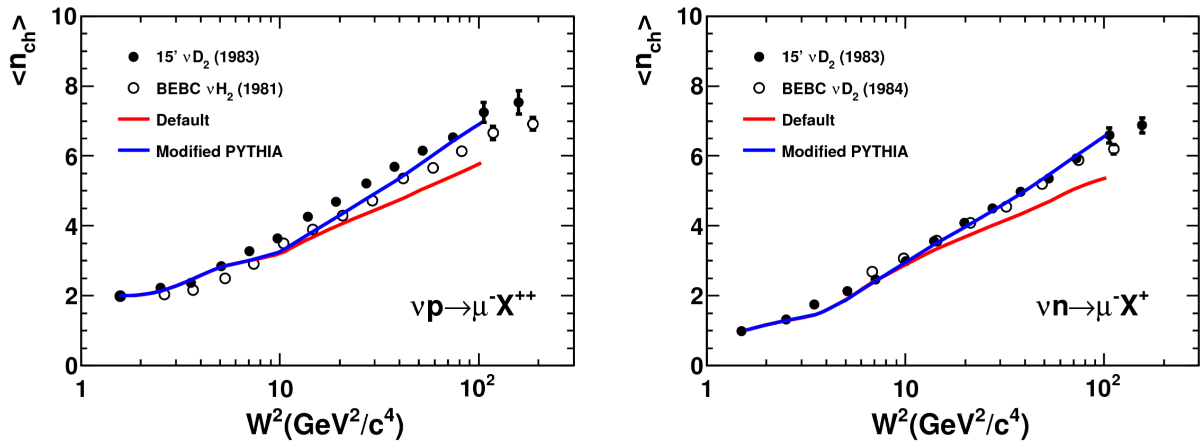
Tuning: current approach and strategy

- **We generally modify the model under one of two conditions:**
  - We learn about developments in the community that suggest a problem with GENIE *and prescribe some kind of solution*
  - We observe strong disagreements between GENIE's prediction and our Near Detector data that can't plausibly be ascribed to another source of uncertainty (like just shown)
- **We generally prefer modifications that:**
  - Have reasonably firm theoretical motivation
  - Are supported by data from external measurements
  - Improve predictions relative to our ND data
- **Choice between changing base model vs. only applying uncertainty** hinges on how many of these ingredients are satisfied
- **We generally focus on specific problems & solutions** rather than liberating all available model knobs in fits to ND data
- **Guided tour of most important components of 2018 tune follows**

Base model: single nucleon



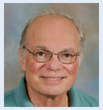
[J.Phys. G42, 115004]



oh… and DIS scattering produces *quarks*
→ need to form hadrons.

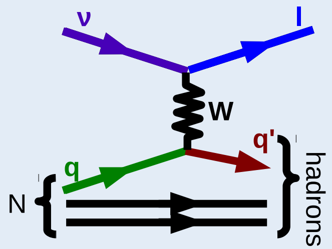
GENIE uses KNO and Pythia for that.
More tuning… more imperfect models…

Inelastic continuum



"Bodek-Yang" model:

- Parton model for lepton-quark scattering
- Uses externally measured nucleon PDFs
- Introduces effective scaling variables to compensate for modifications at low Q^2



Base model: the nucleus

- What initial-state modeling GENIE can do is almost exclusively for *elastic* scattering, with simple "relativistic Fermi gas" (RFG)
  - Suppression factors for Pauli blocking
  - Nucleon Fermi momentum
- Models for it'l state nuclear effects beyond RFG are slowly being added, but:
  - Measurements which can distinguish & constrain them are challenging
  - Modeling dynamics of large A (>4) with large |q| is extremely difficult; different theorists make different compromises
  - Interpolating/extrapolating using existing measurements tricky!
- Final-state interaction models also make various compromises (semi-classical vs. reweightable)

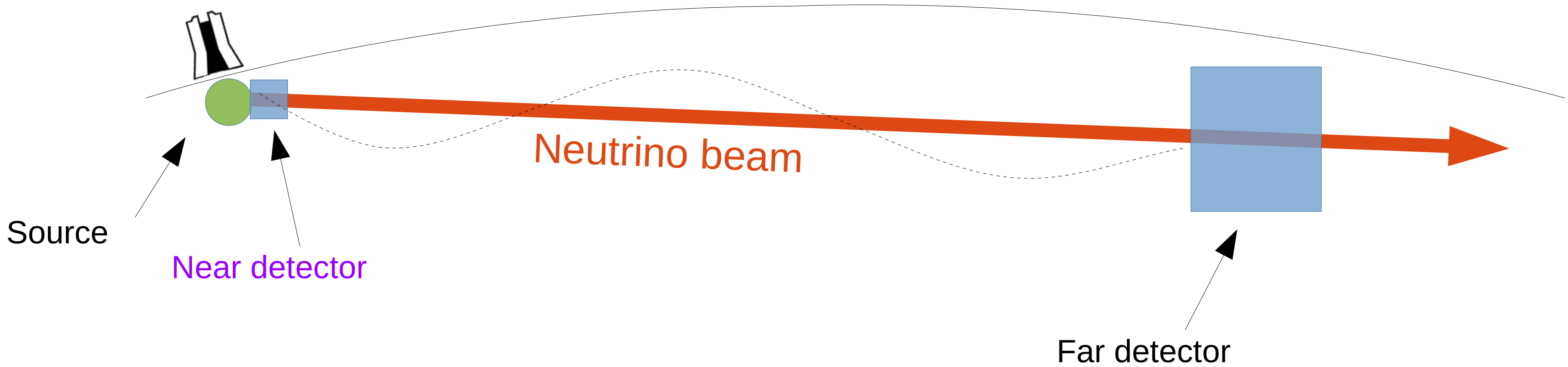
Glaze: **rare processes**
- Pure leptonic: ν+e, inv. μ decay
- (Heavy) flavor modifications to below

Overlayer: **"nuclear effects"**
- Initial-state effects (Fermi mom., Pauli blocking, SRC; shadowing/antishadowing, EMC, ...)
- Multibody operators (MEC)
- Collective excitations (Giant resonances, screening; diffractive)
- Final-state interactions

Substrate: **single nucleon** processes
- Elastic (e.g. $\nu_\mu N \rightarrow \mu N'$)
- Baryon resonance production (e.g. $\nu_\mu N \rightarrow \mu \Delta \rightarrow \mu N \pi$)
- Inelastic continuum (SIS/transition, DIS)

Constraining the prediction: ND extrapolation

The NOvA strategy: “Far/Near ratio”



$$N\left(E_\nu^{rec}\right)=\Phi\left(E_\nu^{true}\right)\times P_{osc}\left(E_\nu^{true}\right)\times\sigma\left(E_\nu^{true},A\right)\times R\left(E_\nu^{true}\right)\times\epsilon\left(\ldots\right)$$

$$N^{ND}\left(E_\nu^{rec}\right)=\Phi\left(E_\nu^{true}\right)\times\sigma\left(E_\nu^{true},A\right)\times R\left(E_\nu^{true}\right)\times\epsilon\left(\ldots\right)$$

Concept:

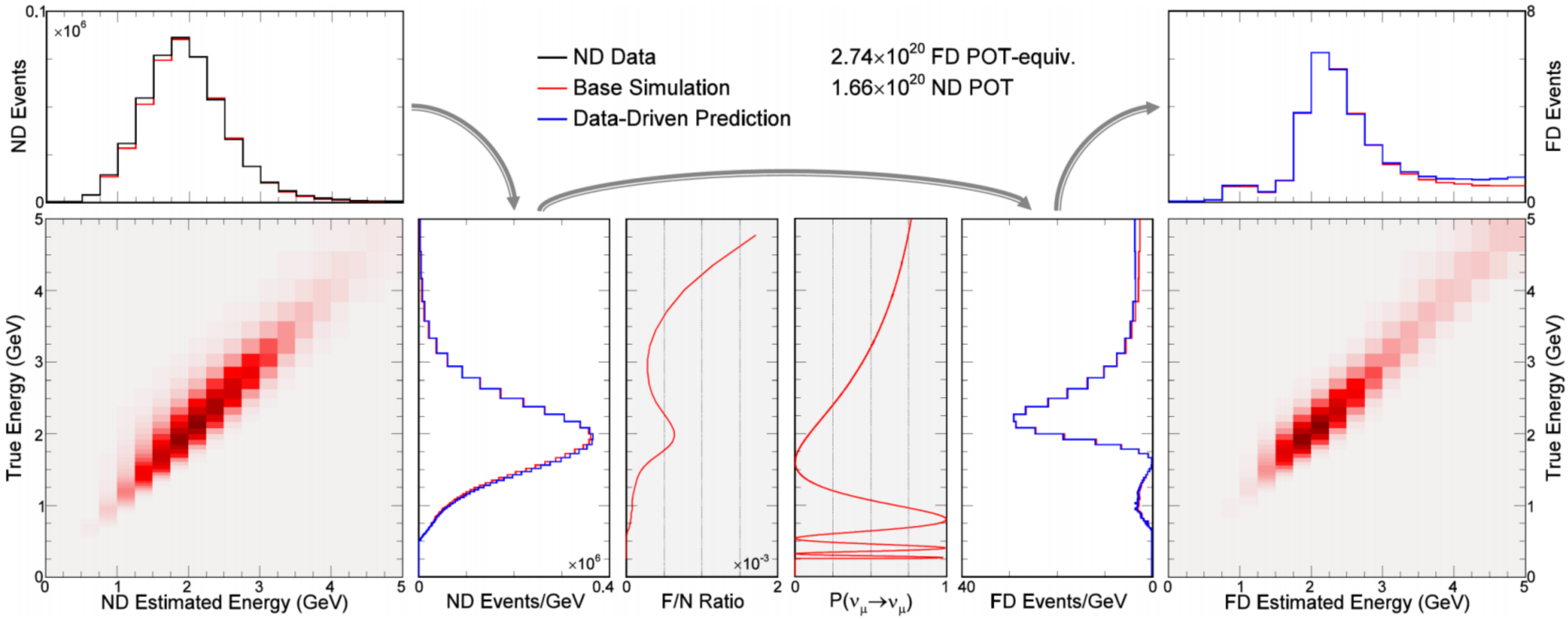
Identical detectors
share all the ingredients
except the oscilliations

→

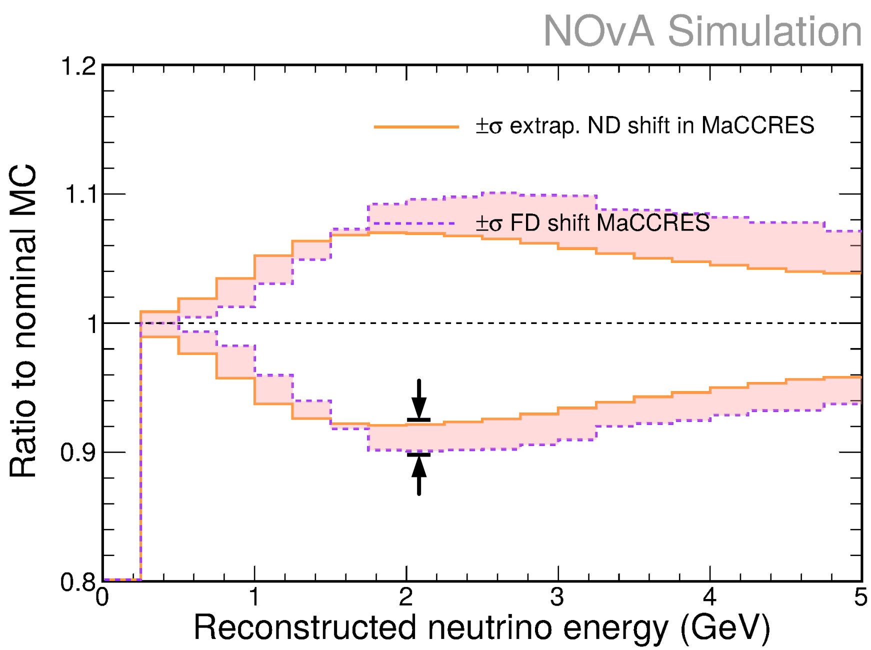
Correct the true *event rate* (Φ×σ×...)
using the ND
and propagate that
(F/N captures geometrical
differences between detectors)

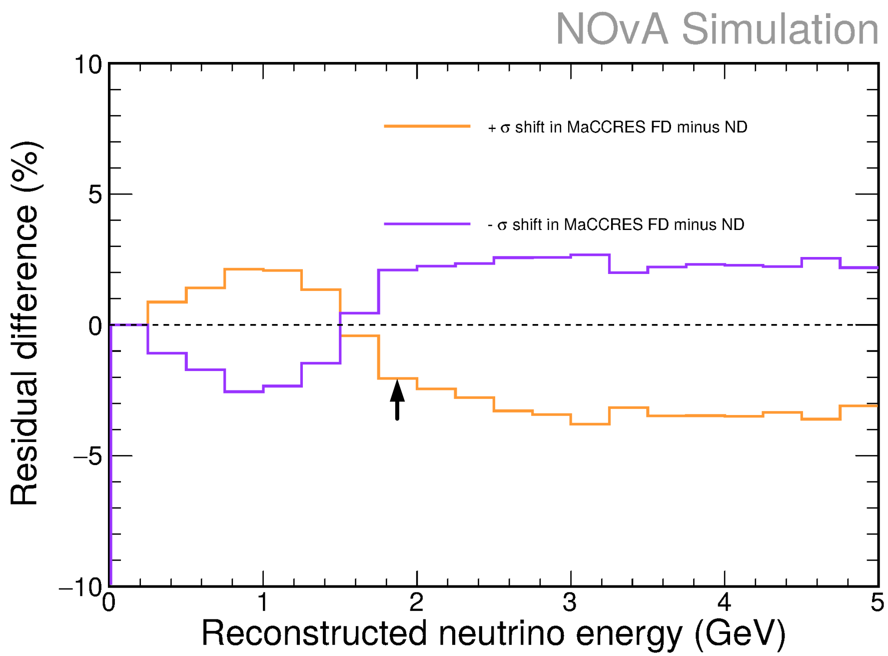
Constraining the prediction: ND extrapolation

The NOvA strategy: “Far/Near ratio”



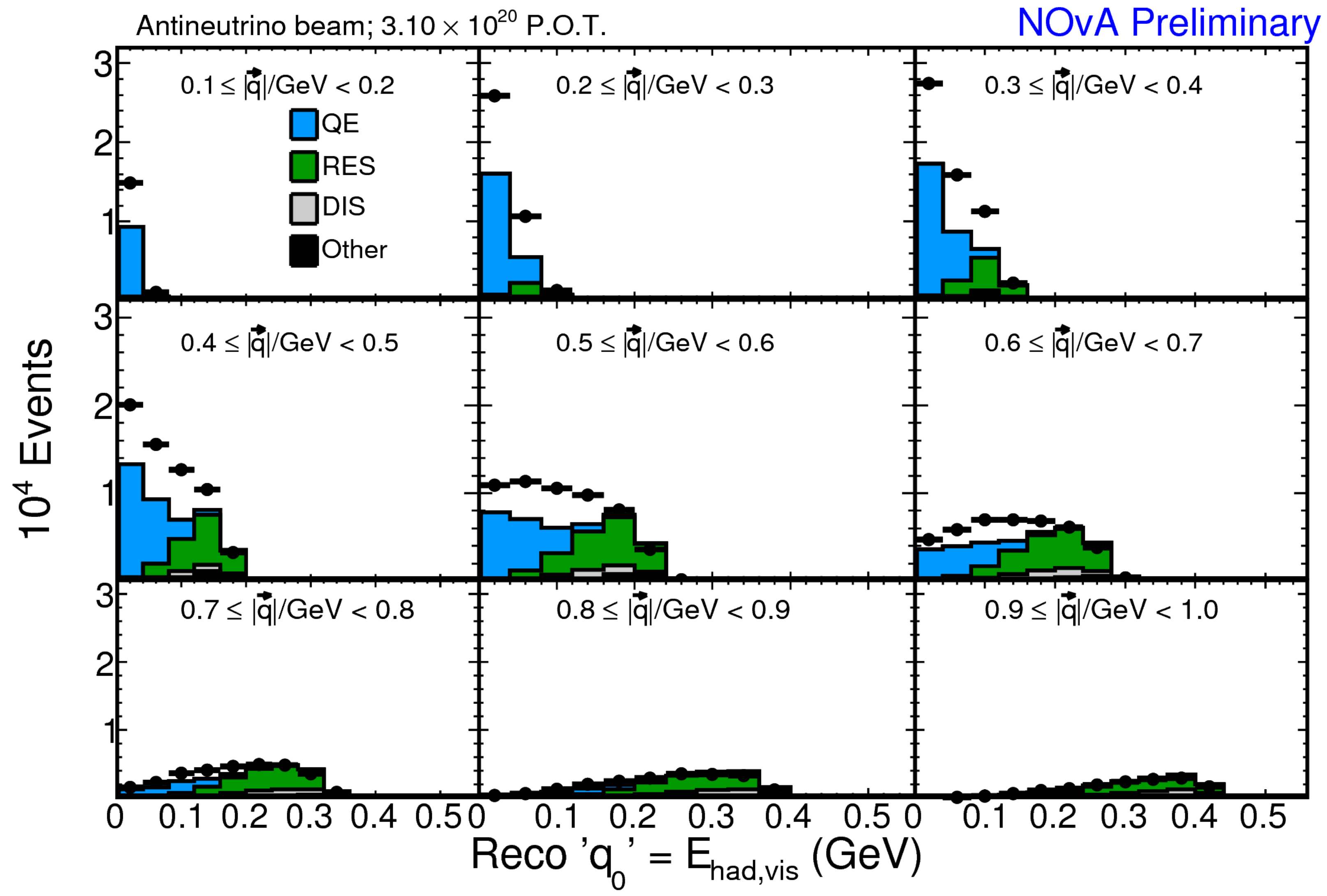
The NOvA experiment: oscillation strategy



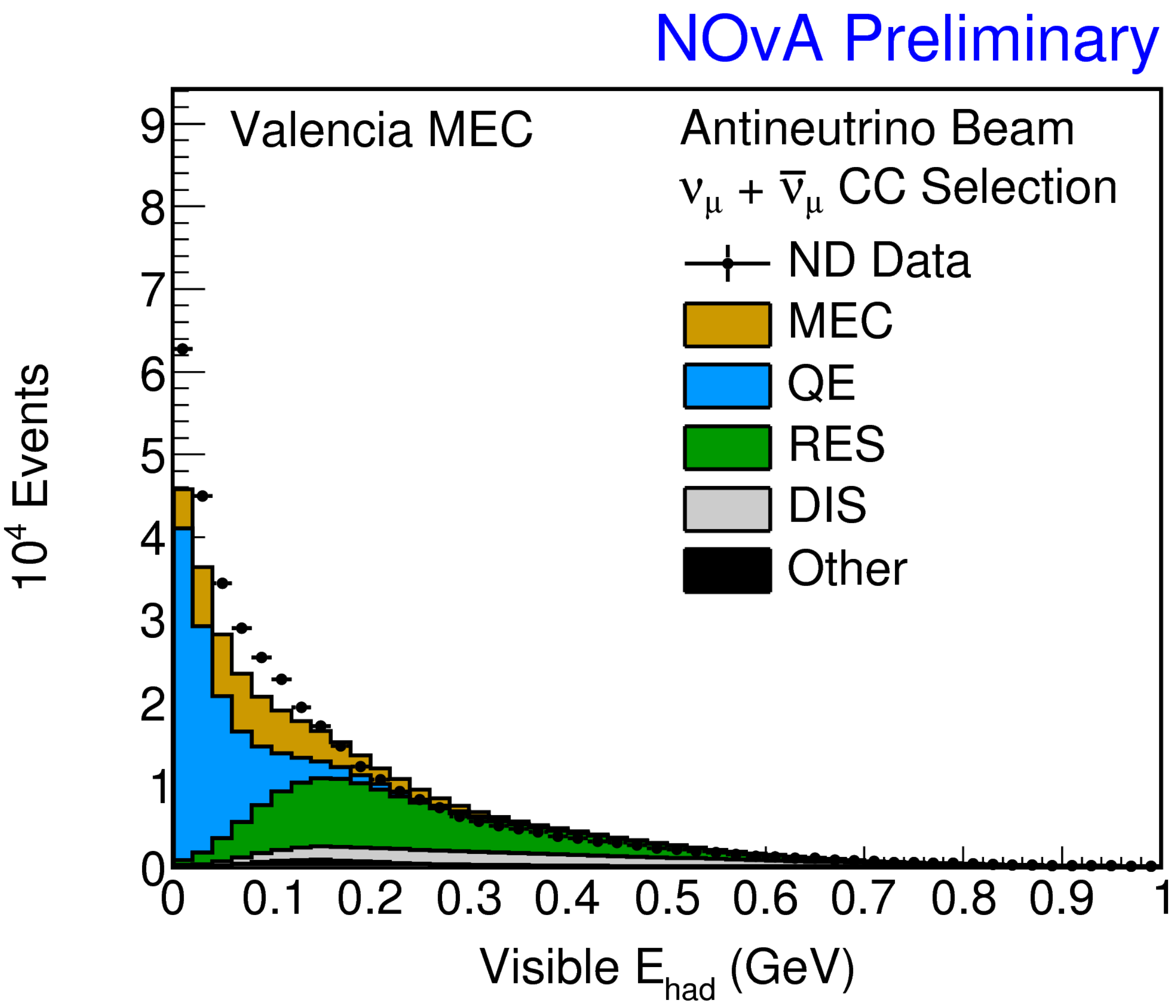


Extrapolation substantially reduces
(but doesn't entirely eliminate)
effect of most cross section uncertainties

Antineutrinos

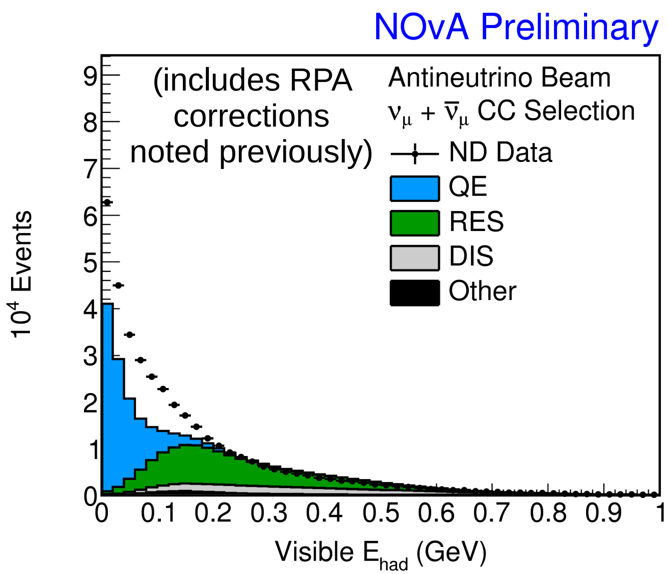


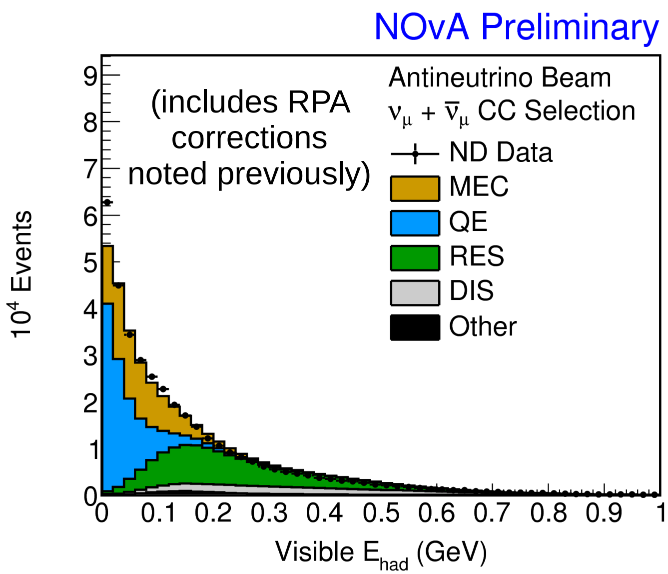
Antineutrinos

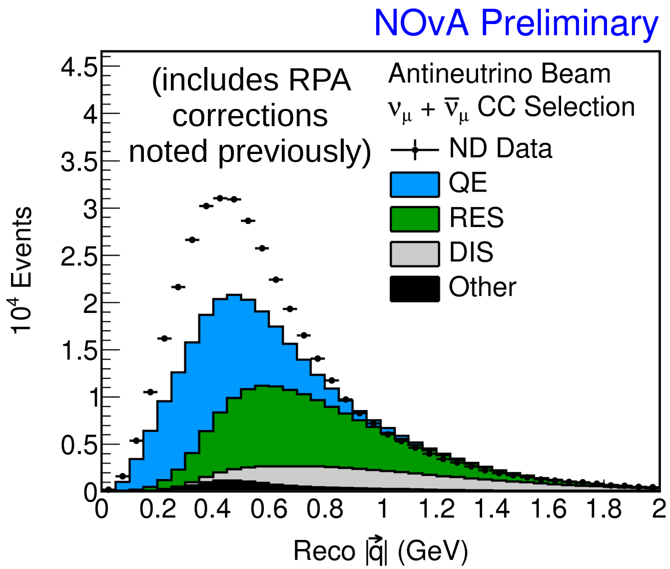


València MEC + RPA QE, RES

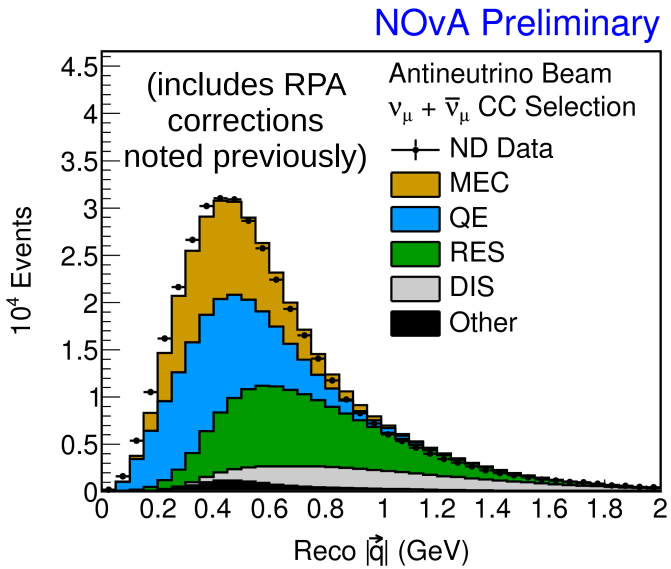
Antineutrinos



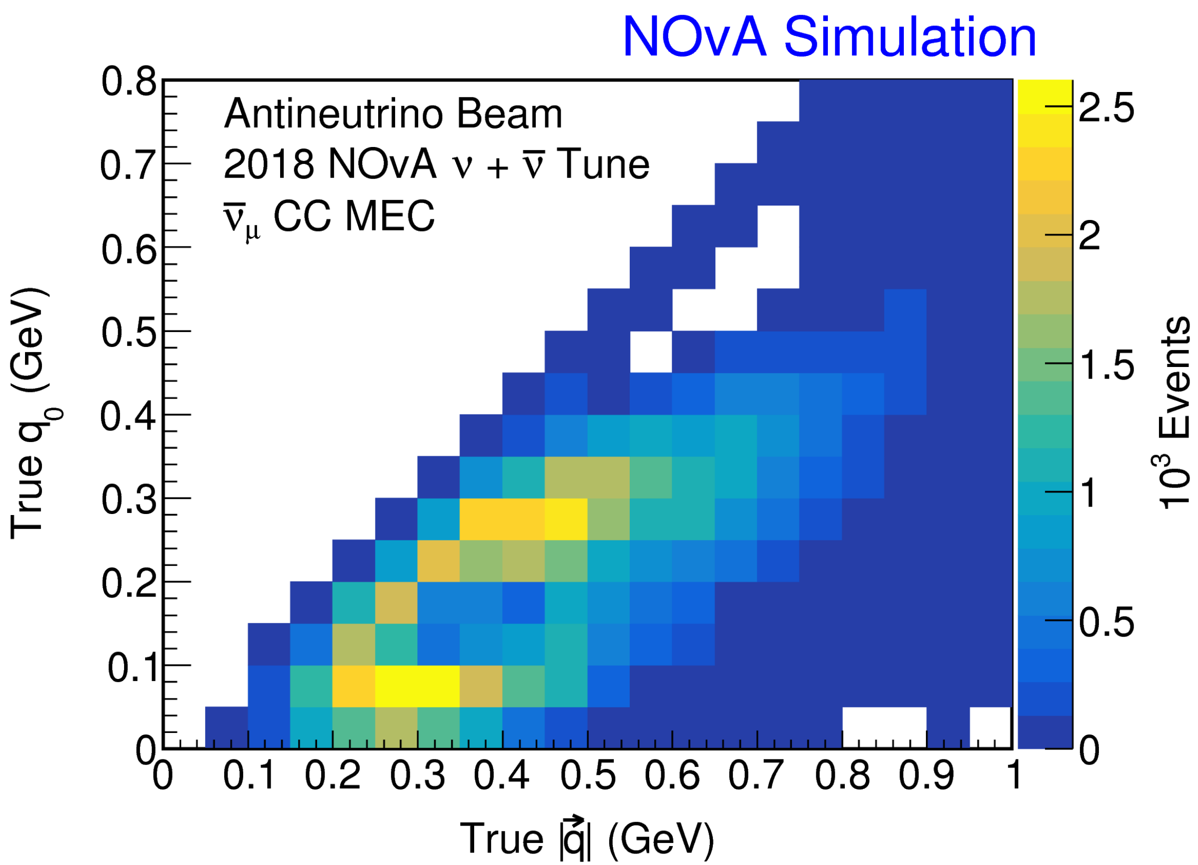


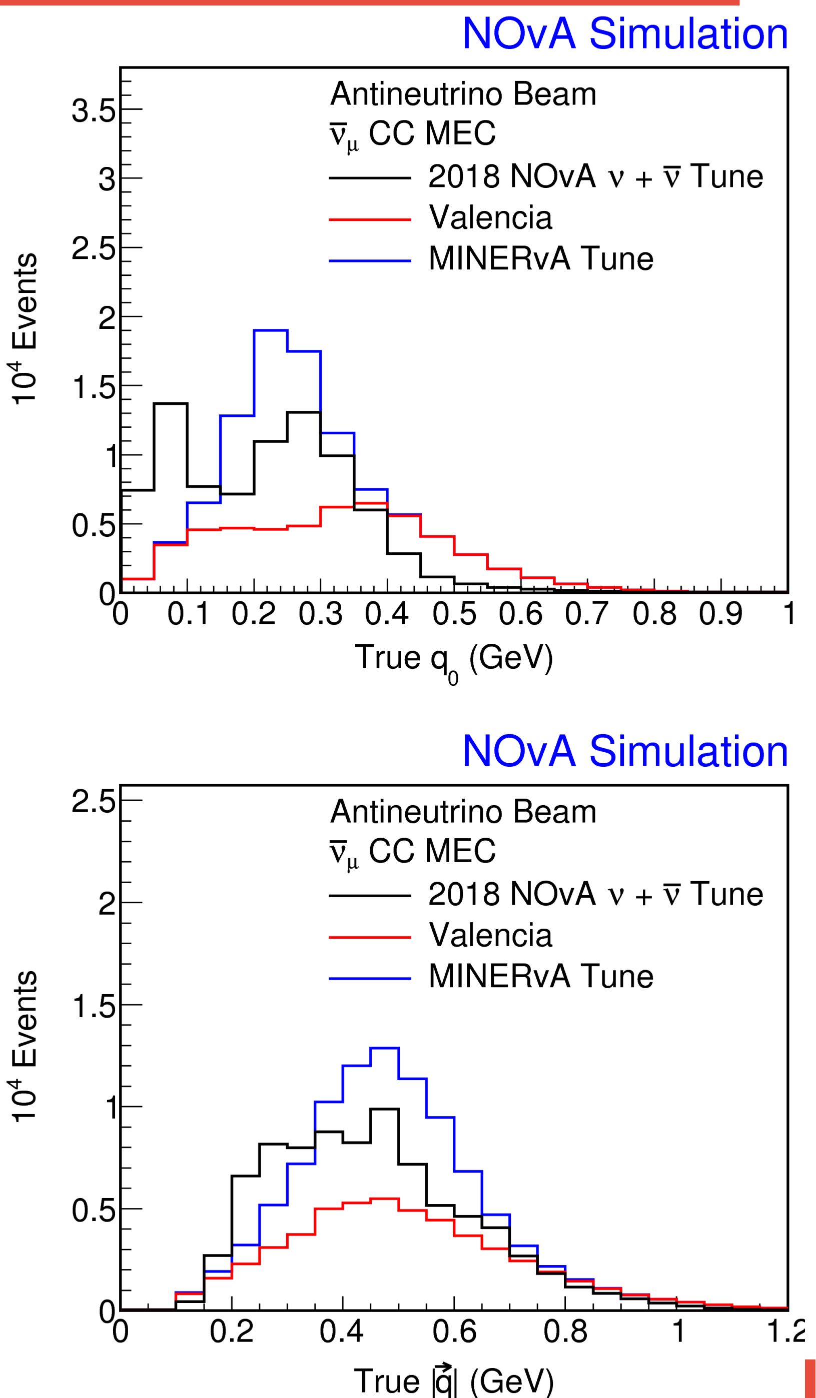


Fitting procedure has slightly more trouble than in FHC b/c none of the MEC models have enough events at low (q0, |**q**|) to reweight (will alter Empirical MEC default in next analysis)



Antineutrinos





Fit results
Even more bimodal than FHC
(maybe suggests RPA correction too strong?)

Antineutrinos