Impact of cross section modeling on NOvA oscillation analyses

on behalf of the NOvA collaboration

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Tufts University

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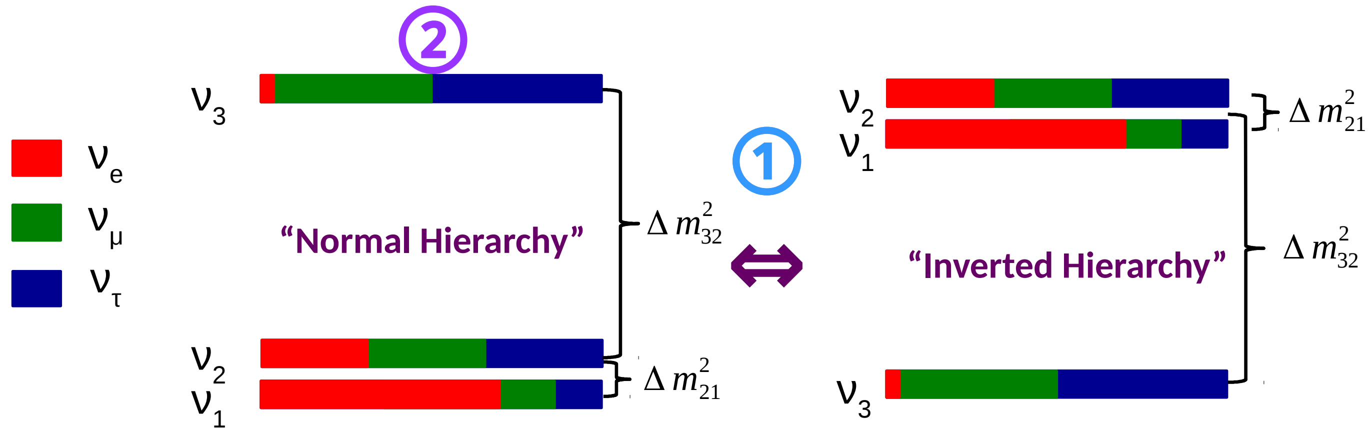
NuInt 2018 (L'Aquila, Italy)

NOvA: ν oscillation physics

① How are the mass eigenstates ordered?

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



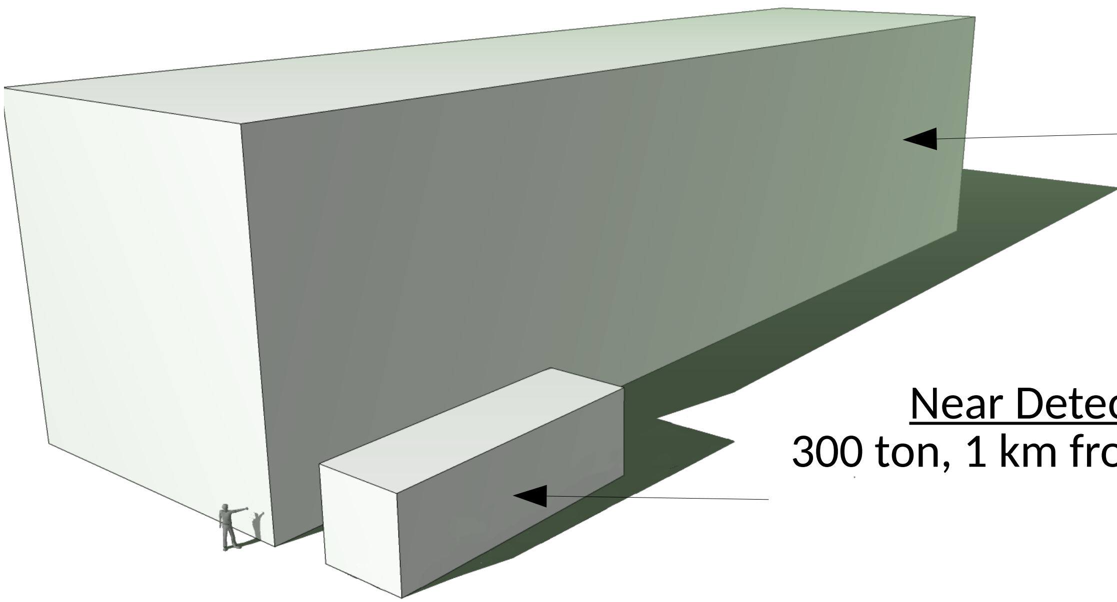
② ③

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

③ Is there CP violation in leptons?

Measuring key parameters in oscillation physics

NOvA: design considerations



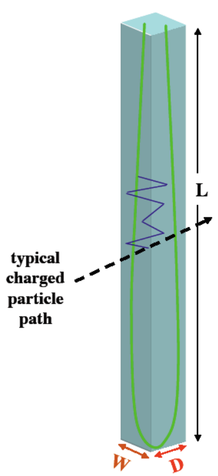
<u>Far Detector</u>
14 kton, 810 km from source

<u>Near Detector</u>
300 ton, 1 km from source

Functionally identical detectors

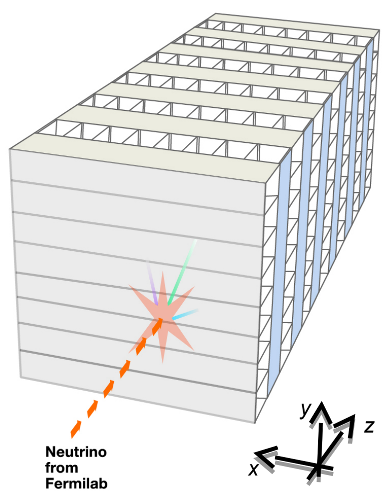
Sampling calorimeter detectors

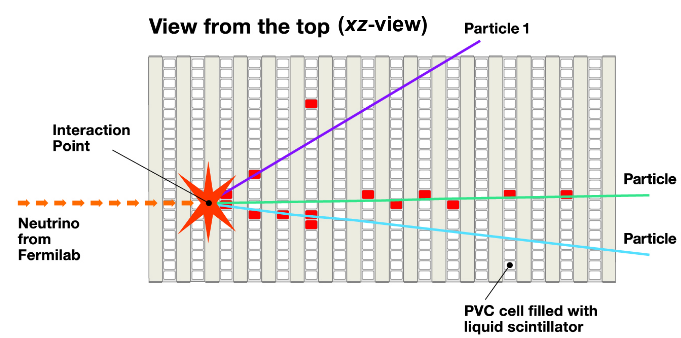
1 Channel

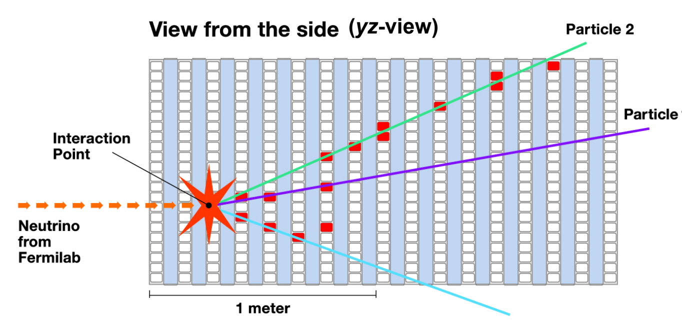


(4cm × 6cm)

stacked in planes

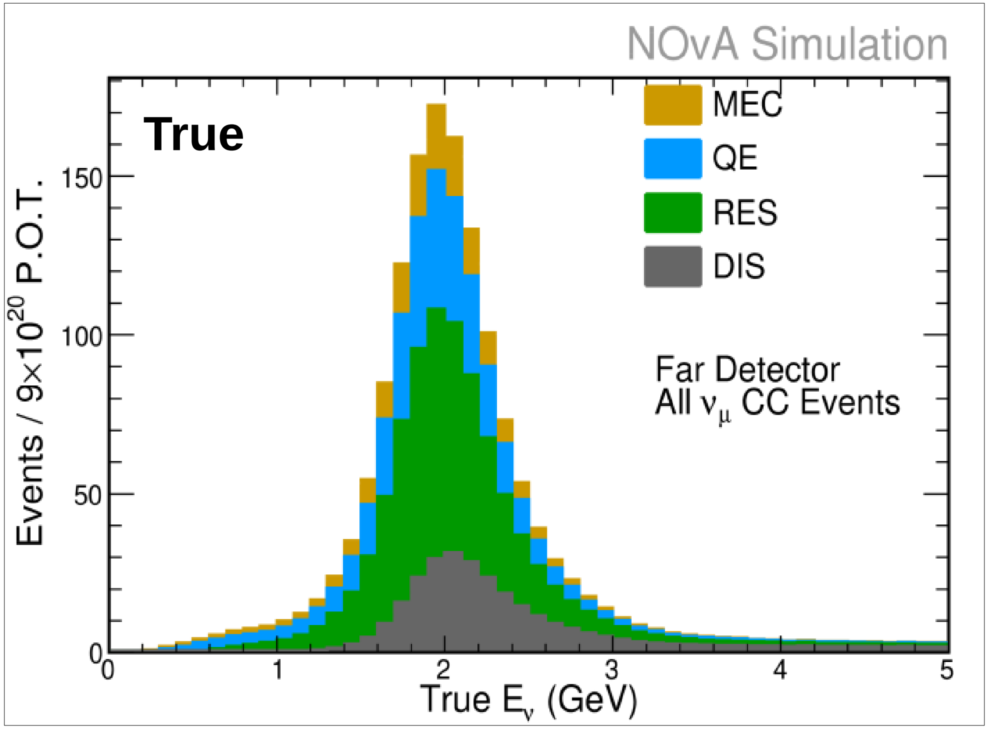






How cross sections enter the story: energy reconstruction

- $P(\nu_\alpha \rightarrow \nu_\beta)$ depends on E_{true}, but detectors measure E_{reco}
- Detectors/reconstruction have different sensitivities to different processes, which have different $E_{true} \leftrightarrow E_{reco}$



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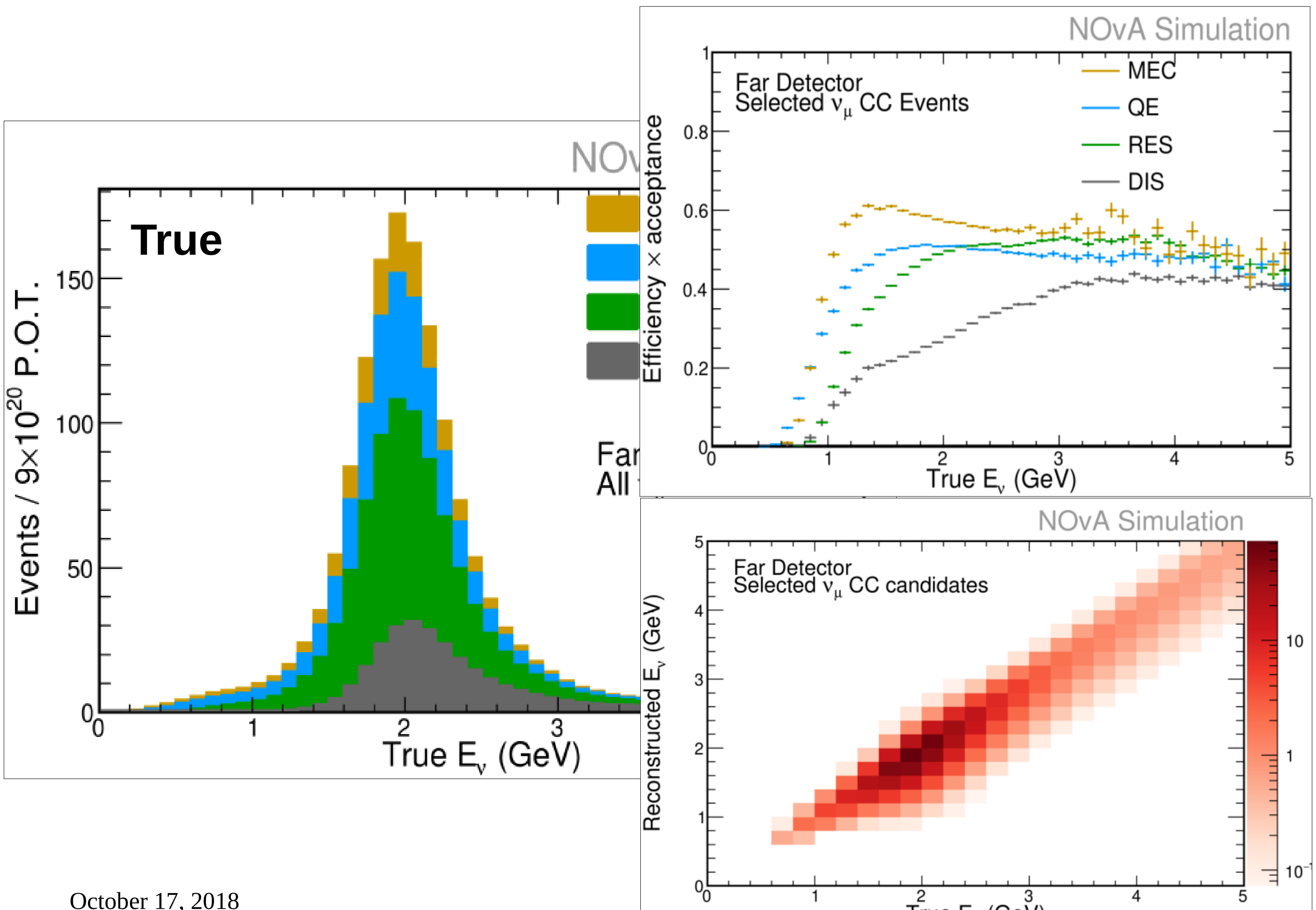

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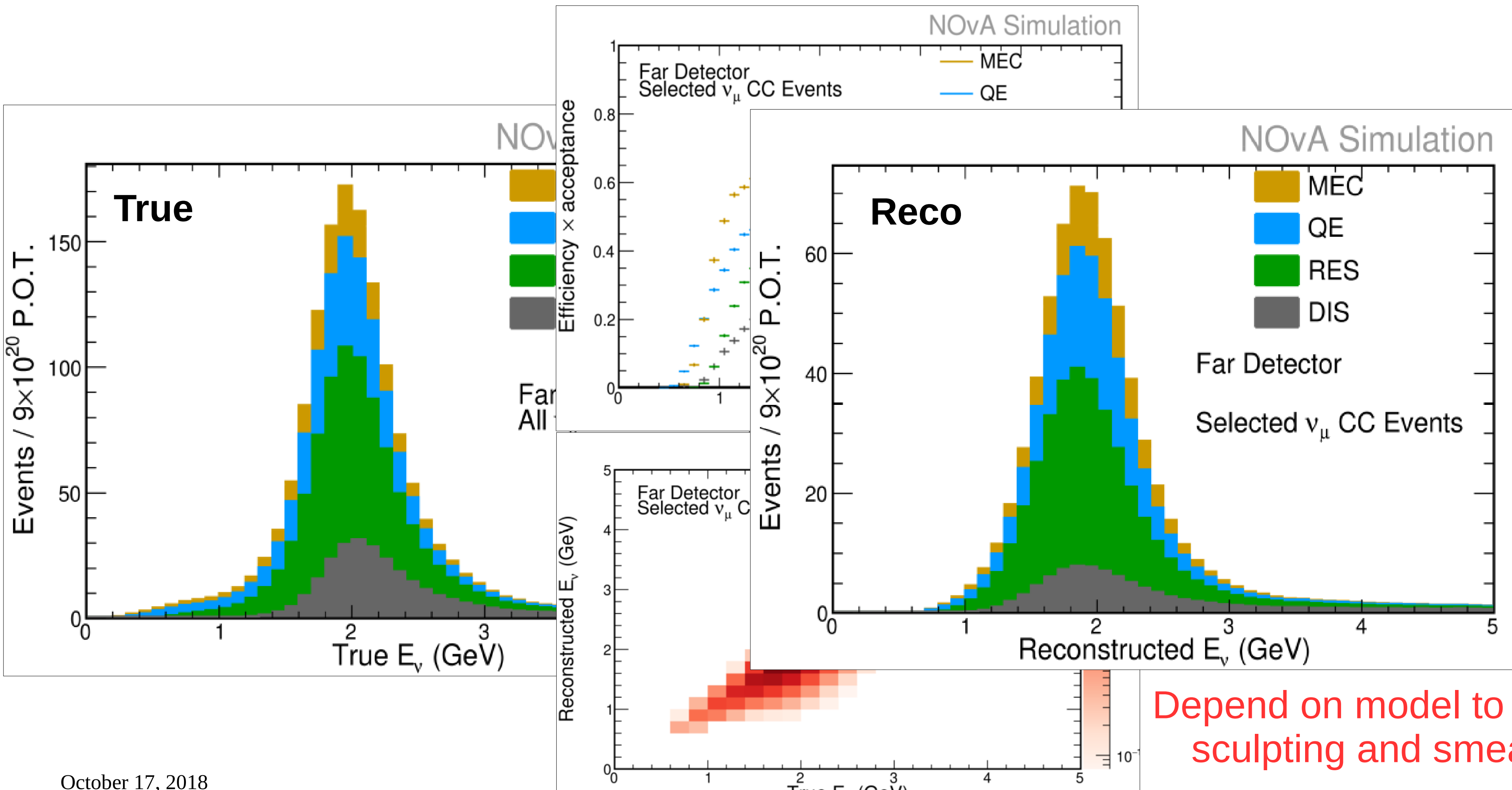
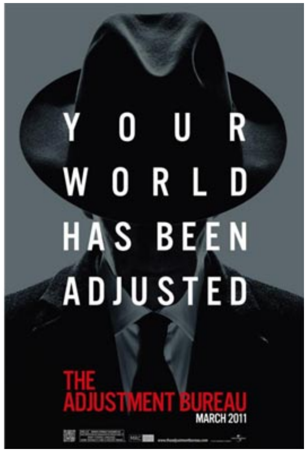


Depend on model to predict sculpting and smearing

Model building

We adjust GENIE 2.12 (base model) based on **theory work** and **other experiments' data:** thanks to the hard work of many in this room!
(fuller discussion in J. Wolcott, FNAL Neutrino Seminar, Apr. 23 2018; paper forthcoming)

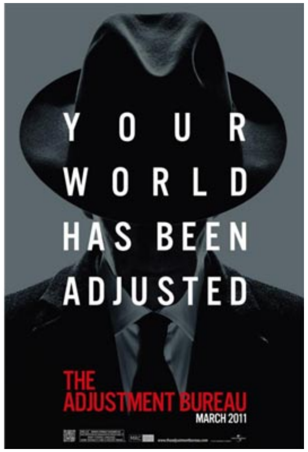


Free-nucleon model

Use **dipole axial FF with M_A^{QE} = 1.04 ± 0.05 GeV** based on error-weighted mean we calculated from bubble chamber data
[collected in PRD **93**, 113015]
(GENIE default: 0.99 GeV)

Z-expansion in our future...

Model building



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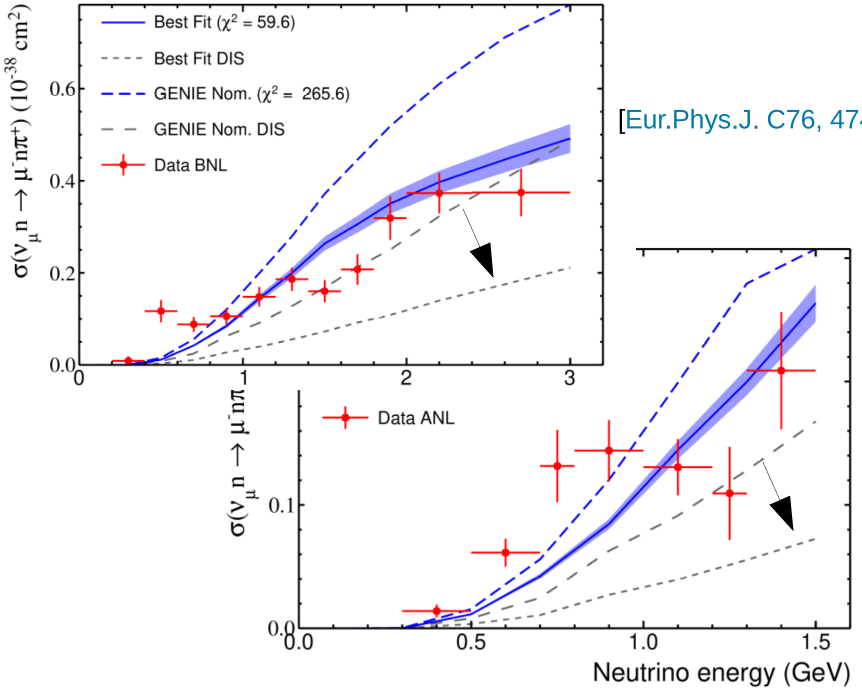
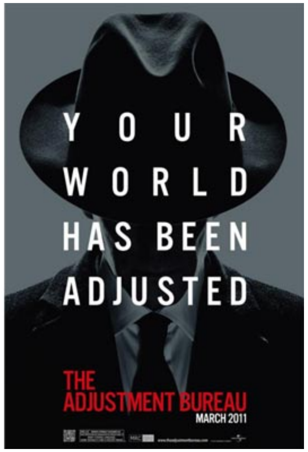


[Eur.Phys.J. C76, 474]

Nonresonant 1π⁺ production from neutrons needs to be **reduced by ~50%** based on updated fits to free-nucleon data

New since 2017

Model building



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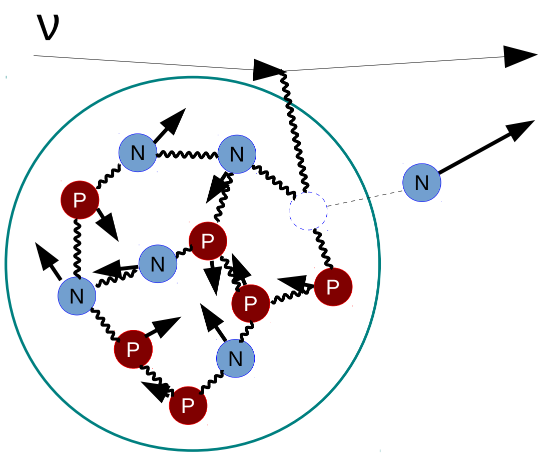
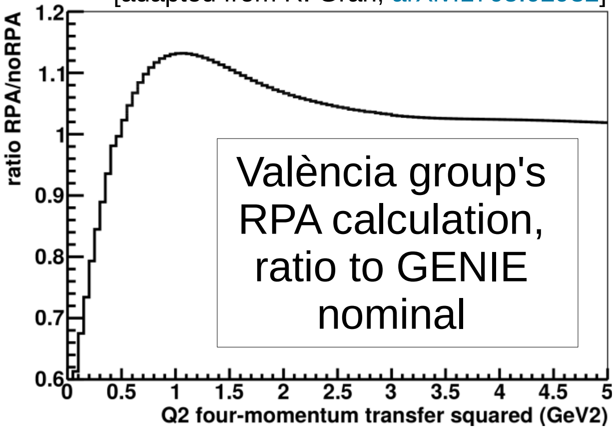


Effective nuclear "screening" from collective excitations: treated with **RPA.**

We use Valencia group calculation for QE;
also use Q^2 shape for RES
based on suppression noticed in external and NOvA data

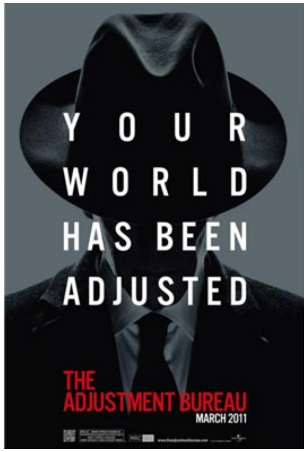
[adapted from R. Gran, arXiv:1705.02932]



Nuclear model

New since 2017

Model building



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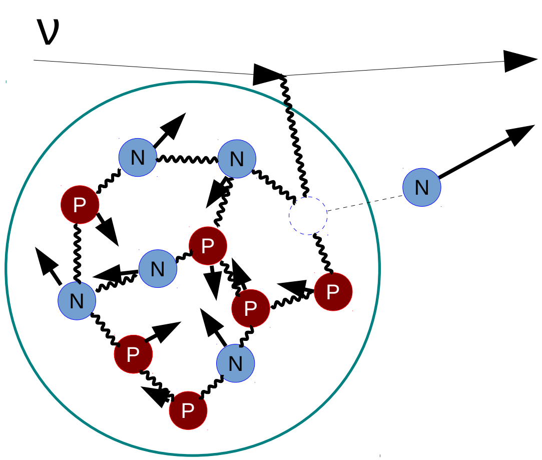

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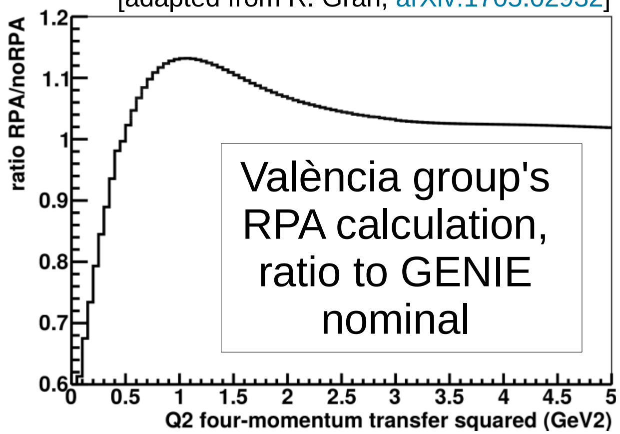
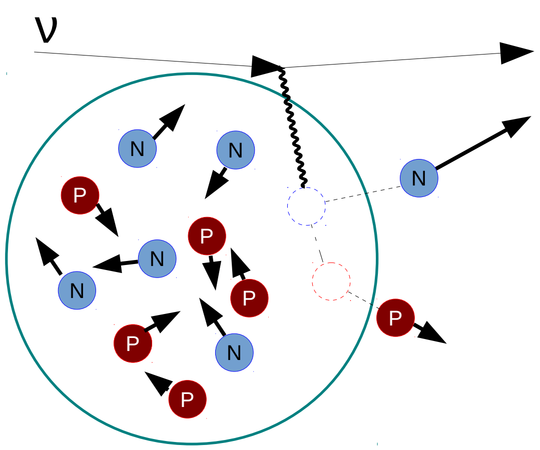
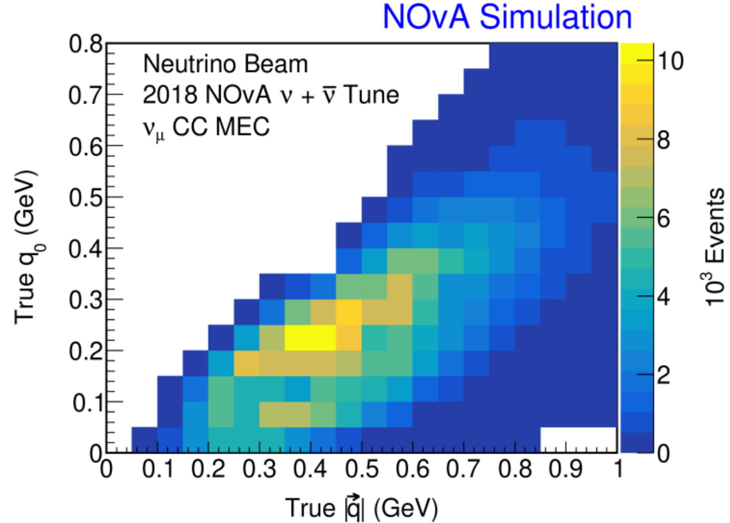




Multinucleon knockout (2p2h)

We enable GENIE "Empirical MEC", retune it based on our data. Uncertainties from fits under different assumptions.



Nuclear model

Evaluating cross section uncertainties

Depend heavily on GENIE's reweight system...

Primary process uncertainties

QE: M_A, Vector FF, Pauli supp...

RES: M_A, M_V, Δ decay isotropy...

DIS: Bodek-Yang parameters, transition region ("non-resonant background" scale), …

COH: Rein-Sehgal M_A, R_0, ...

Final-state model (hA) uncertainties

Nucleon, pion elastic, inelastic, chg ex., abs. reaction probabilities

Hadron mean free paths

(~50 reweight knobs in all)

…and build custom knobs for our growing library of GENIE 'adjustments':

MEC model for **2p2h** (q^μ shape, E_ν shape, nn/np composition)

RPA-QE (based on València treatment; histograms from R. Gran)

RES-Q^2 (conservative "on" vs "off")

In practice:

ν_μ disappearance

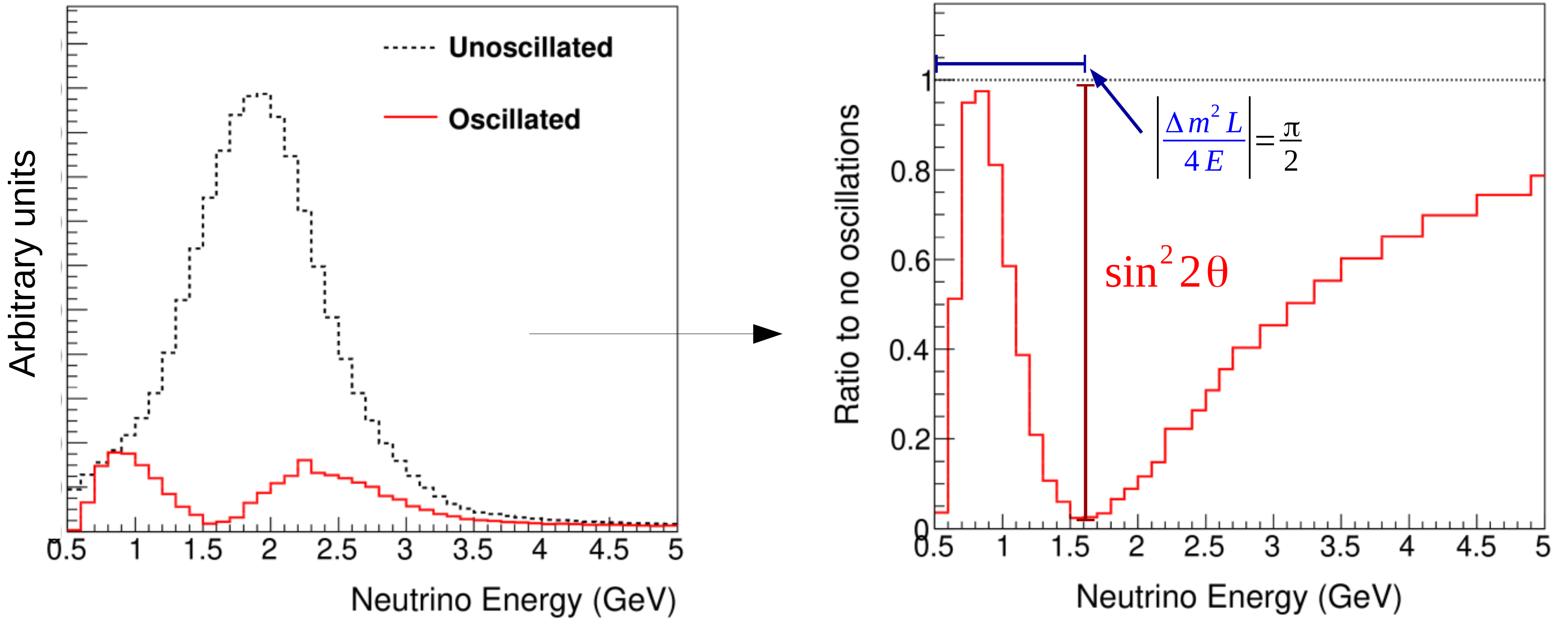
[a worked example]

ν_μ disappearance

$$P_{\nu_\alpha \to \nu_\beta} \approx \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

How far away from the source you build your detector (L)

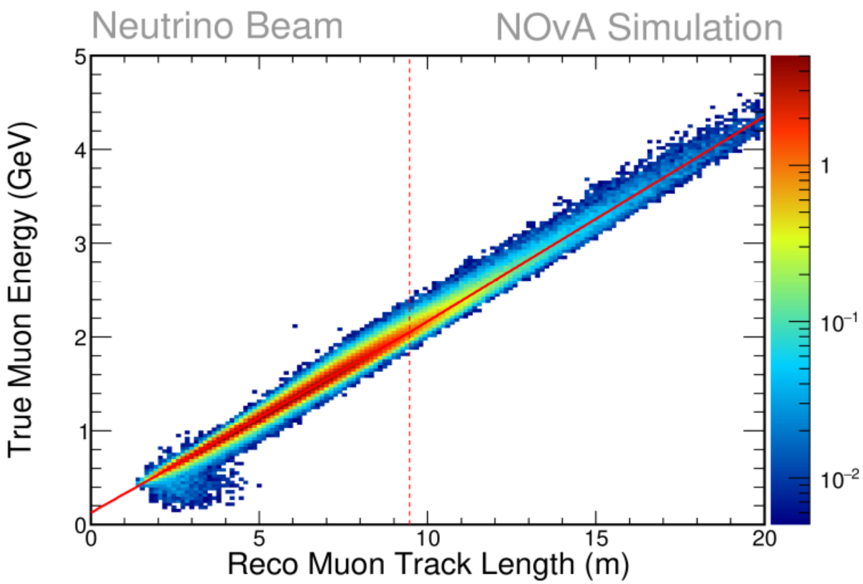
Energy spectrum of your neutrino beam (E)



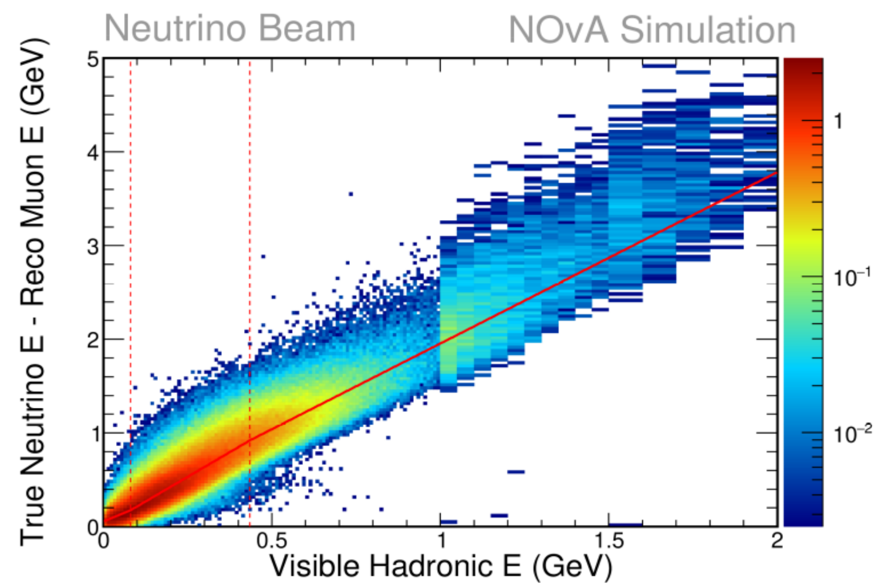
Goal: measure the location and strength of the “oscillation dip” relative to no-oscillations prediction

ν_μ disappearance: energy reconstruction

E_ν = E_{lep} + E_{had}



(3% resolution)

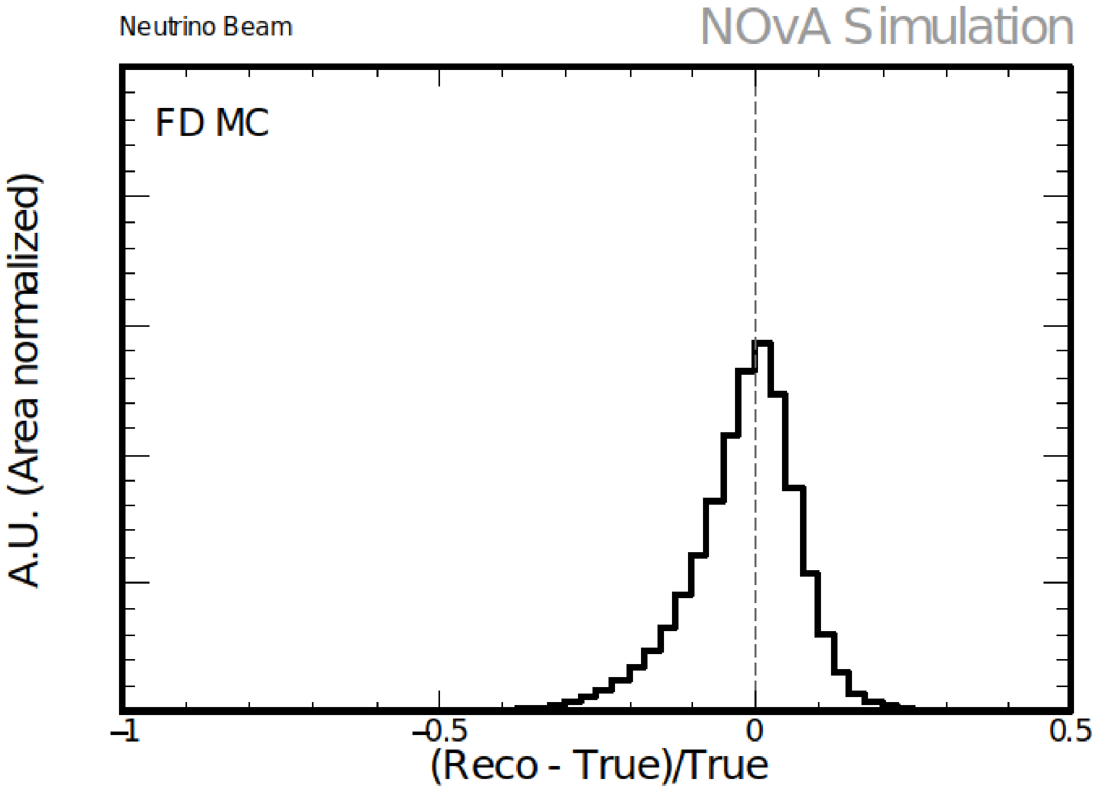


25% resolution, ν
26% resolution, $\bar{\nu}$

Calibrate muon track length to true E_μ, then remaining visible energy to (true E_ν – reco E_μ).

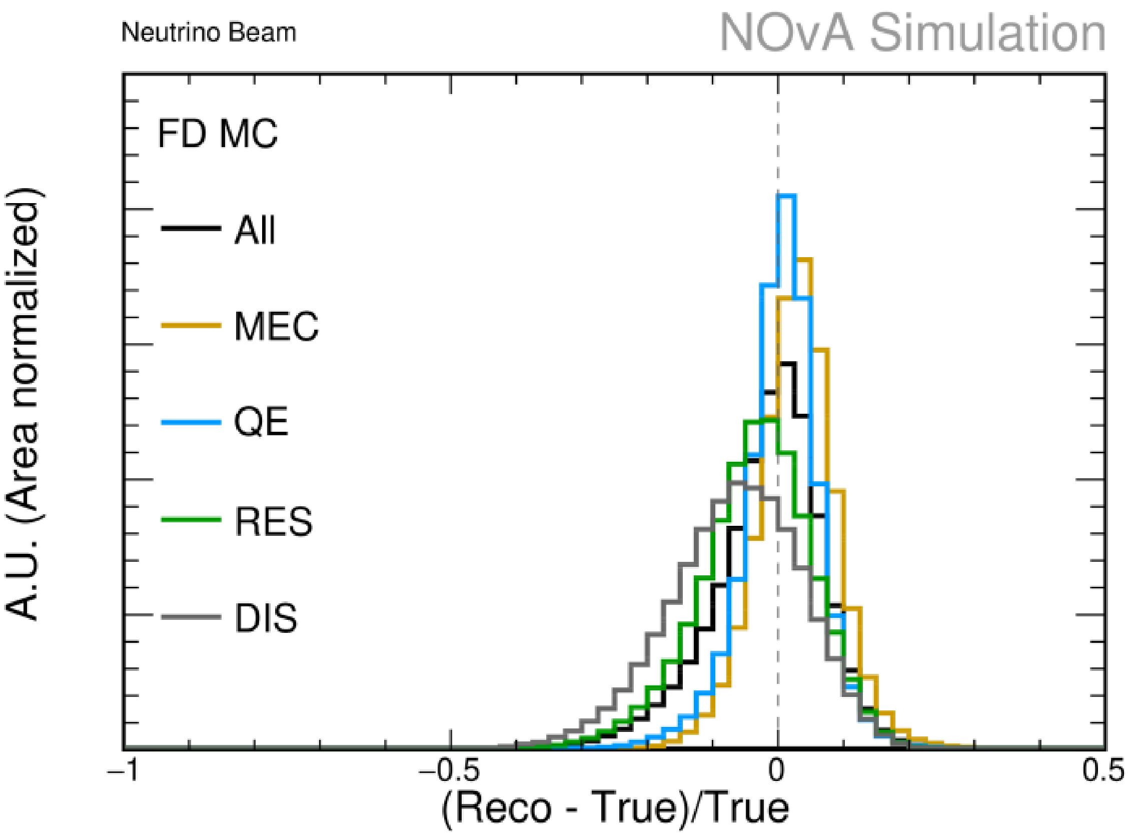
Calorimetric (not kinematic) energy reconstruction

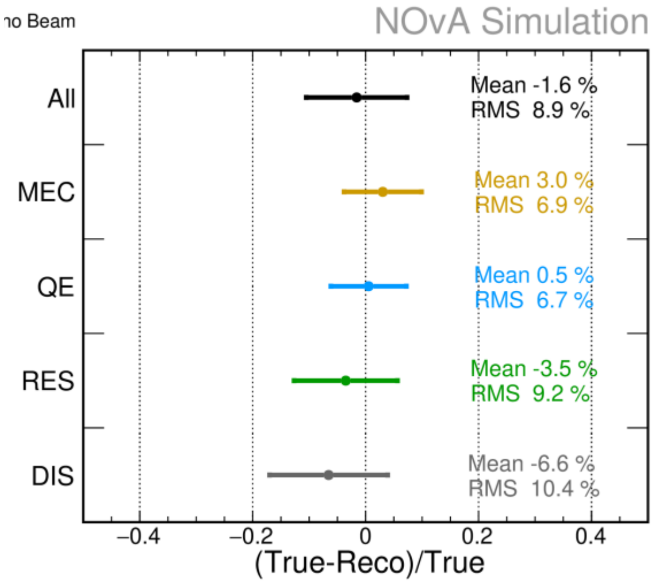
ν_μ disappearance: energy reconstruction



Nominal resolution on E_ν ~ 9%.

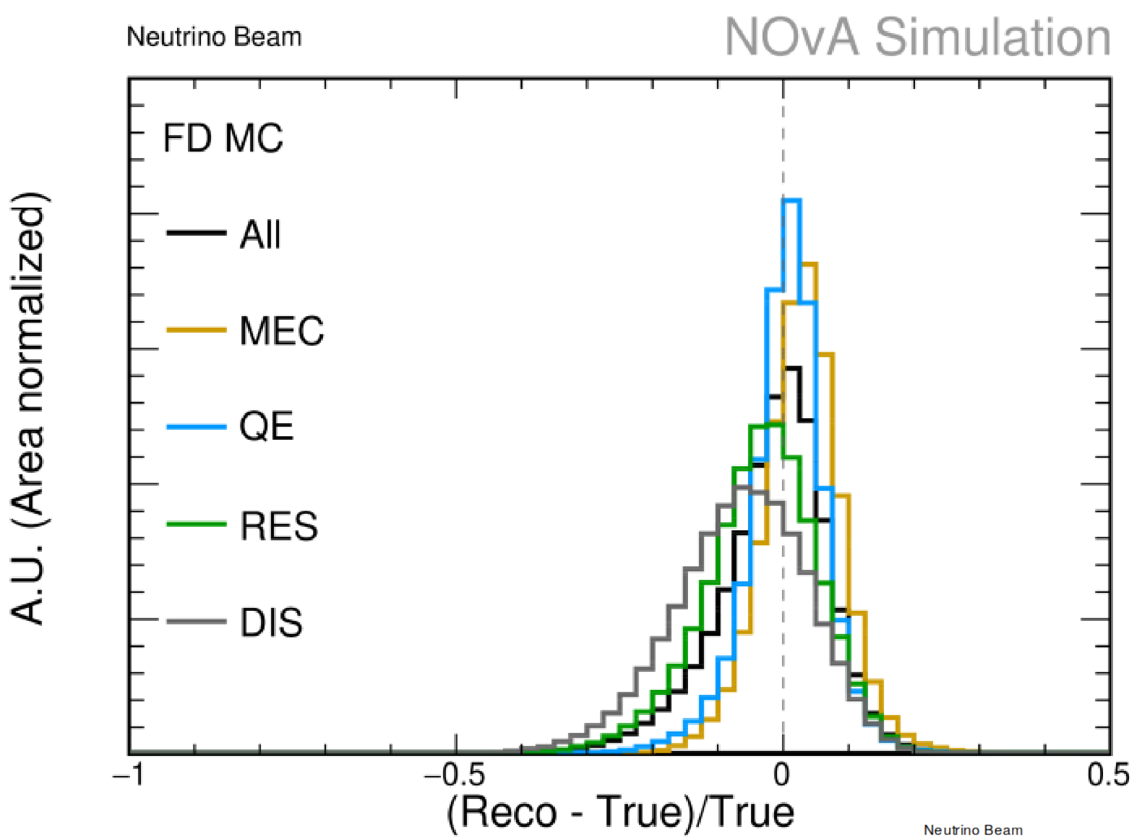
ν_μ disappearance: energy reconstruction

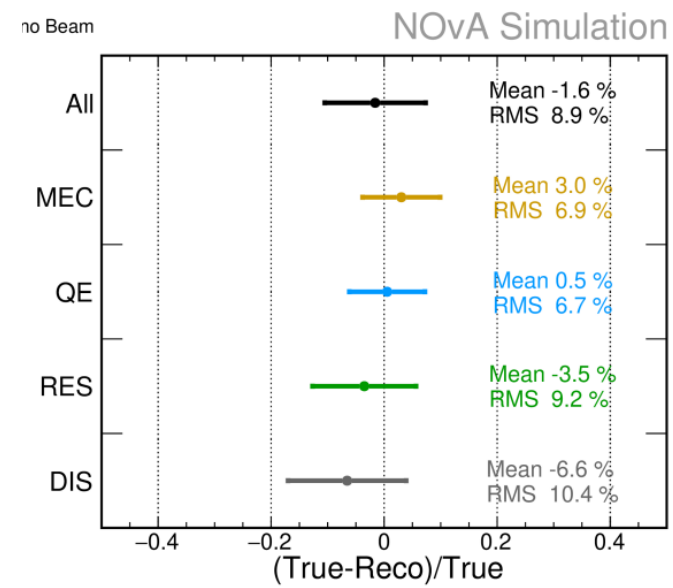




Nominal resolution on E_ν ~ 9%; different by reaction

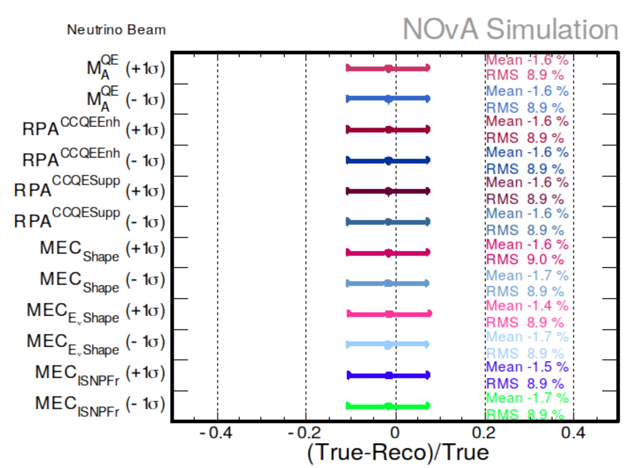
ν_μ disappearance: energy reconstruction

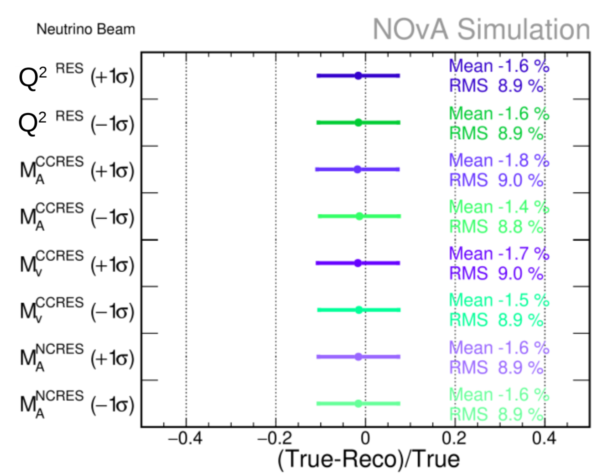




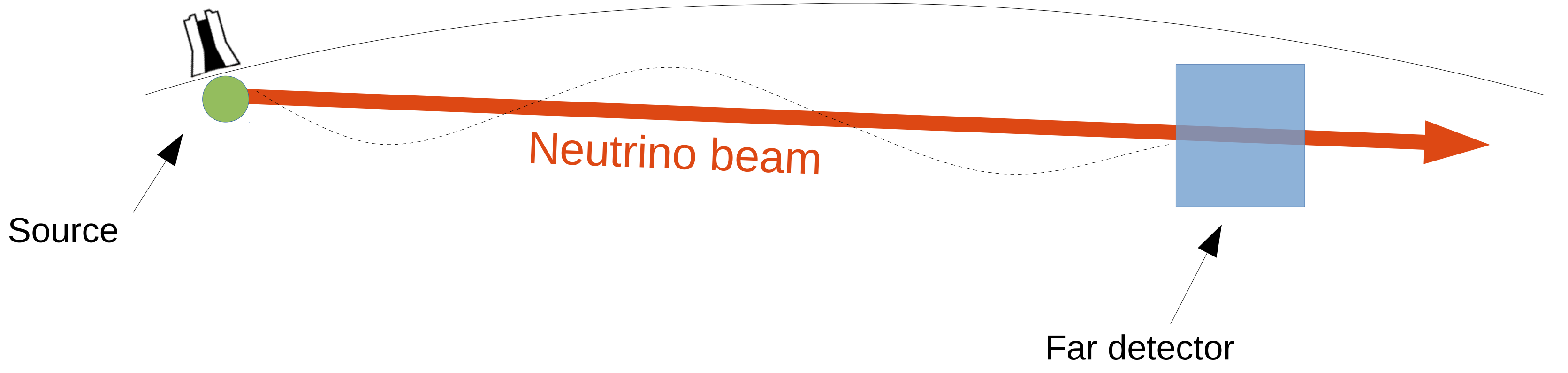
Nominal resolution on E_ν ~ 9%.

Despite sculpting effect, calorimeter-style detectors ensure **cross section systematics don't significantly degrade energy resolution**





Near detectors

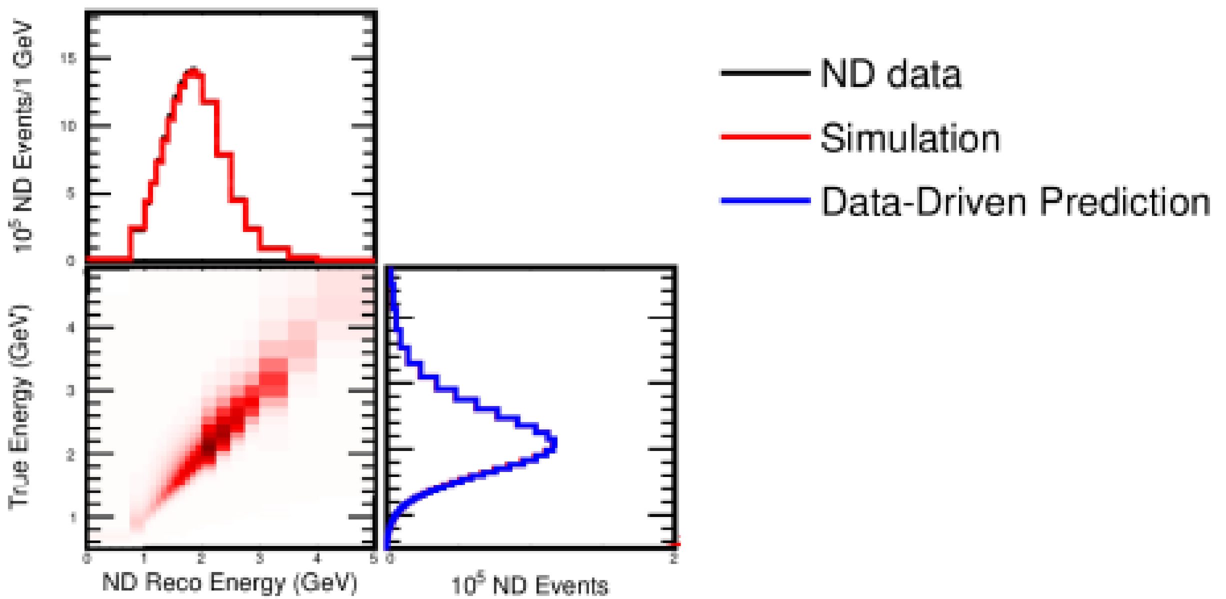


Want to measure oscillation probability.
Many other variables...

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

ν_μ disappearance: “extrapolation”

To produce a data-driven prediction at FD, based on ND:



True energy distribution is corrected so that reconstructed data & MC agree at the ND...

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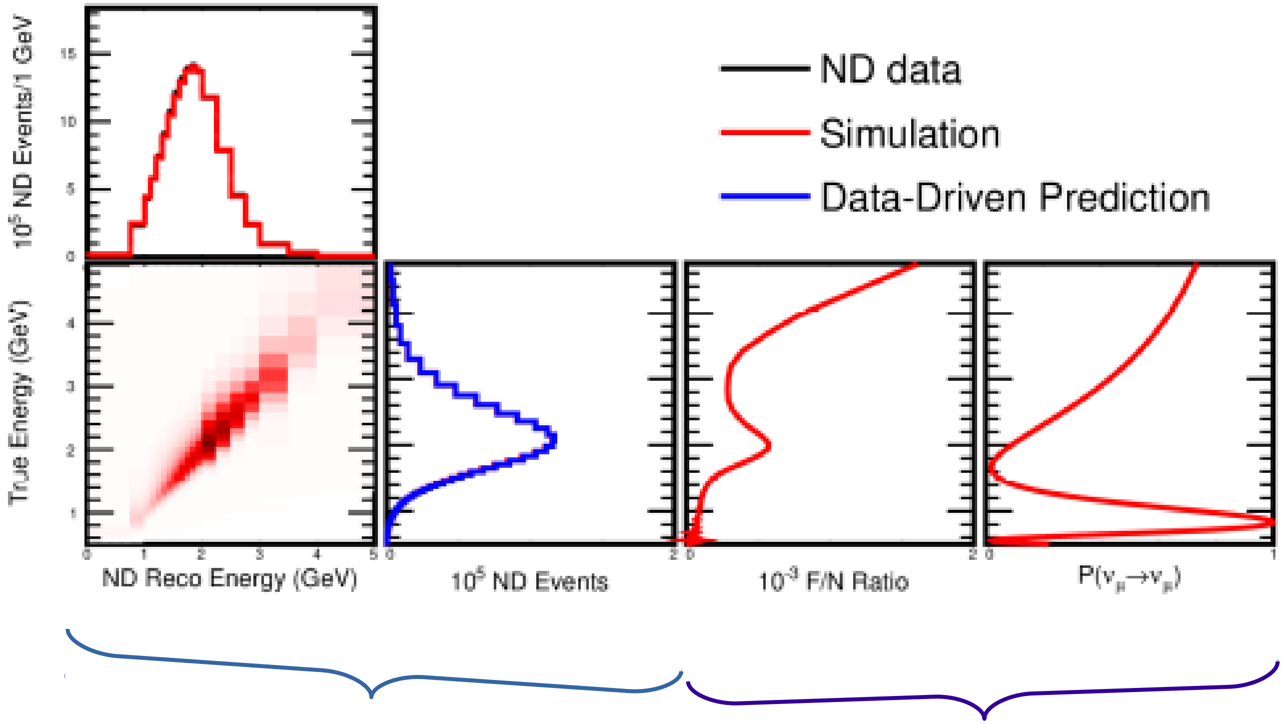

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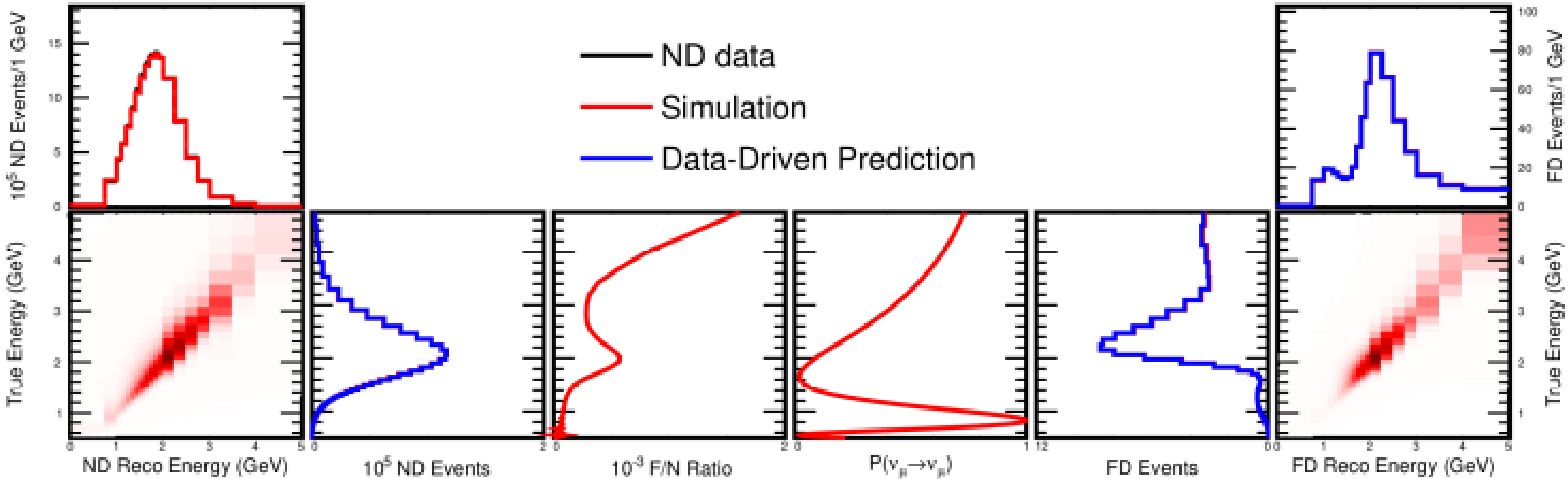


True energy distribution is corrected so that reconstructed data & MC agree at the ND...

…modified true energy distribution is propagated through predicted geometric beam dispersion & acceptance ratio, oscillations...

… and “extrapolated” reconstructed energy distribution computed to compare to data

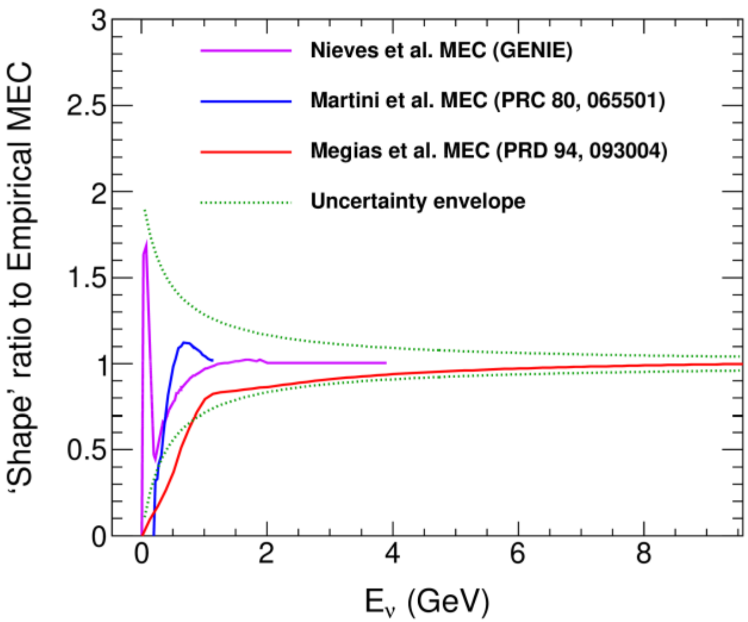
New since 2017

Illustrating XS systematics: MEC

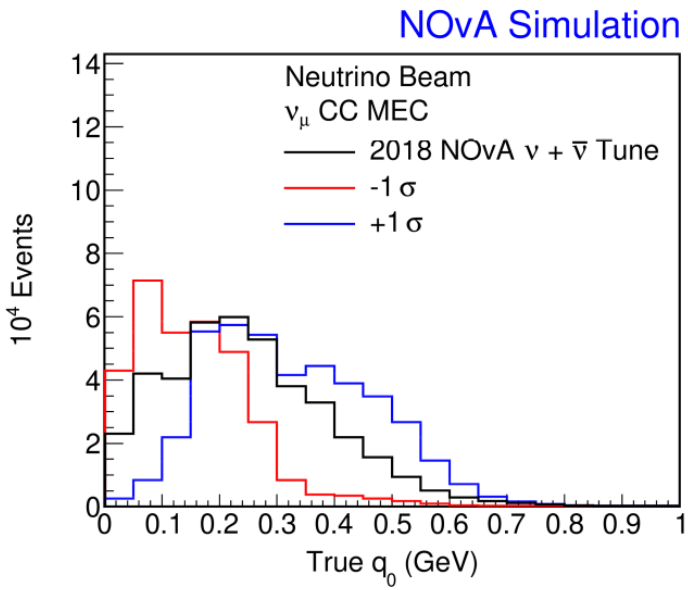
Examine this procedure through the lens of reaction of interest:

2p2h
via
Meson Exchange Currents
(GENIE 'Empirical MEC' w/ ND tuning)

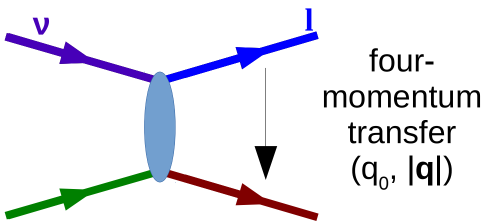
Illustrate behavior through two different knobs:



Neutrino energy dependence
(brackets theoretical models)



Four-momentum transfer dependence
(bounds our fits)



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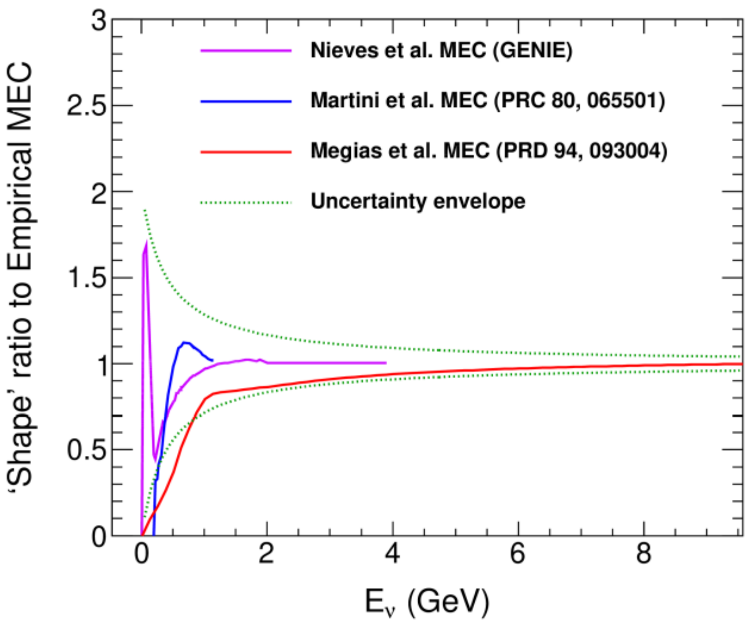

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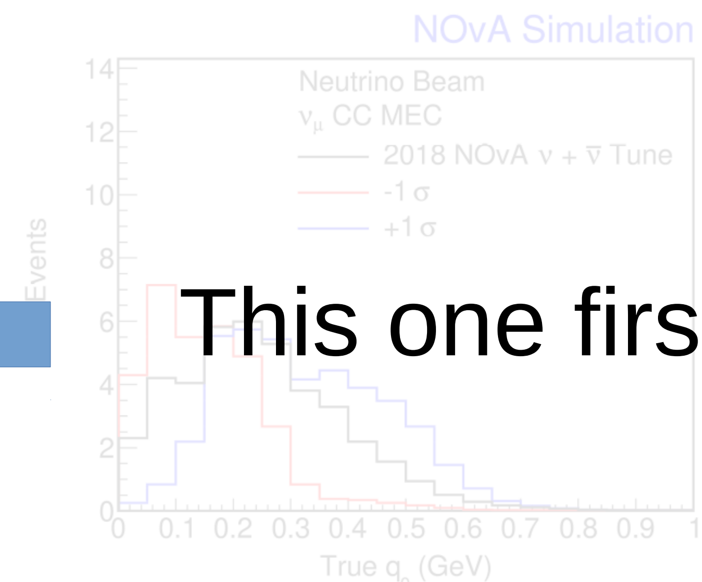
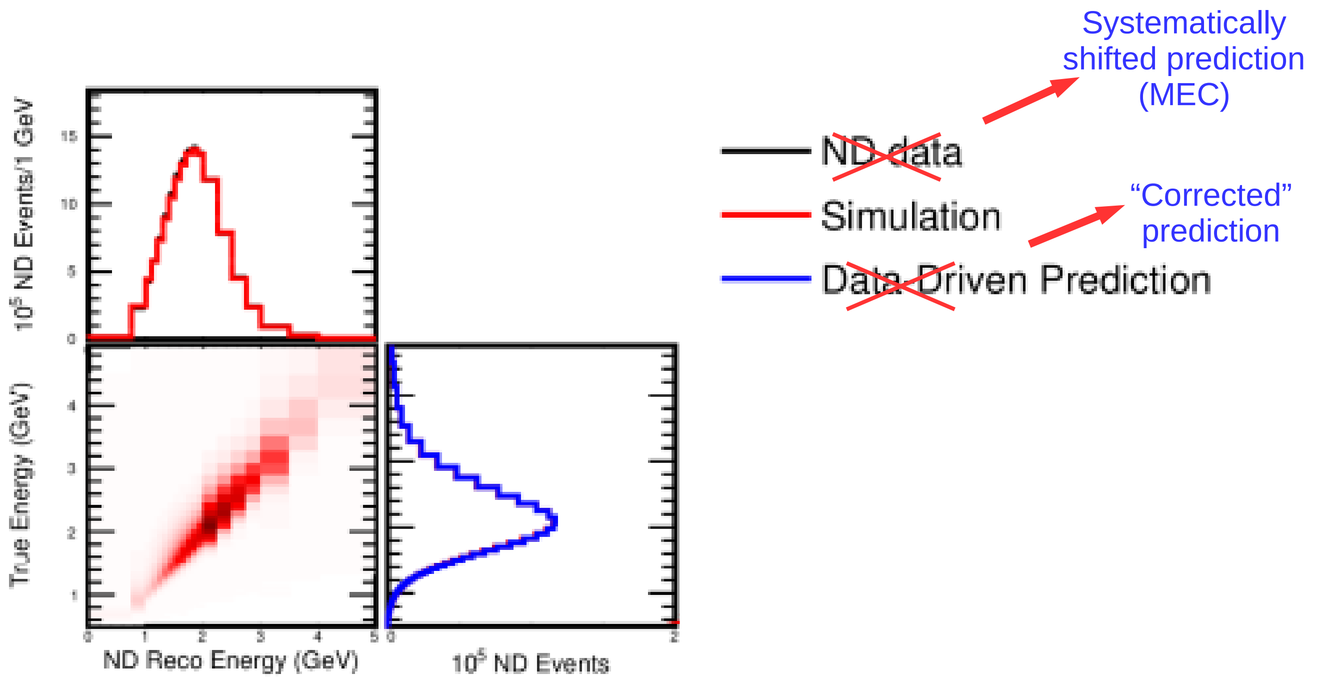


This one first

Four-momentum transfer dependence
(bounds our fits)

Testing extrapolation

To examine the effect of extrapolation:



① Replace "ND Data" with "ND prediction under systematic shift".

(Asks: "if data exhibits this effect, and we use baseline simulation, how well does extrapolation compensate?")

Testing extrapolation

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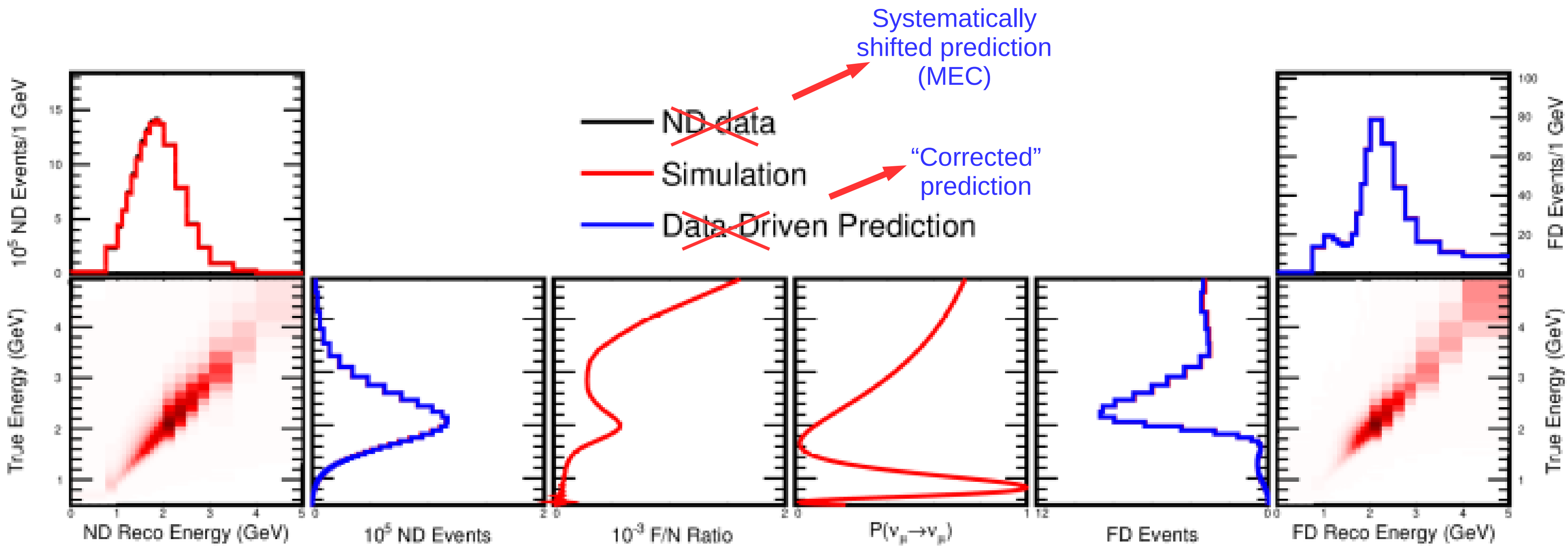

② Transport "corrected" prediction through extrapolation process

Testing extrapolation

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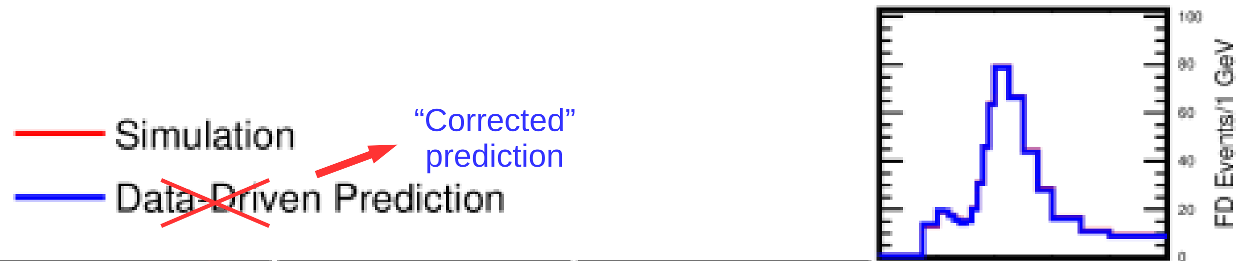
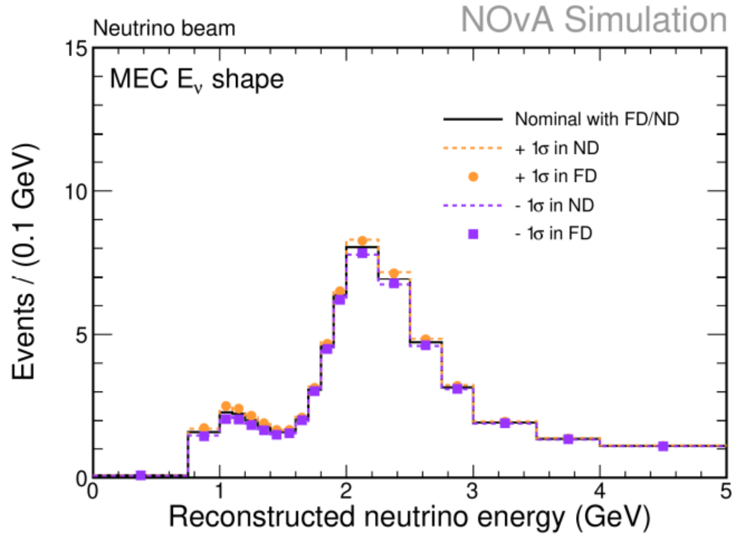
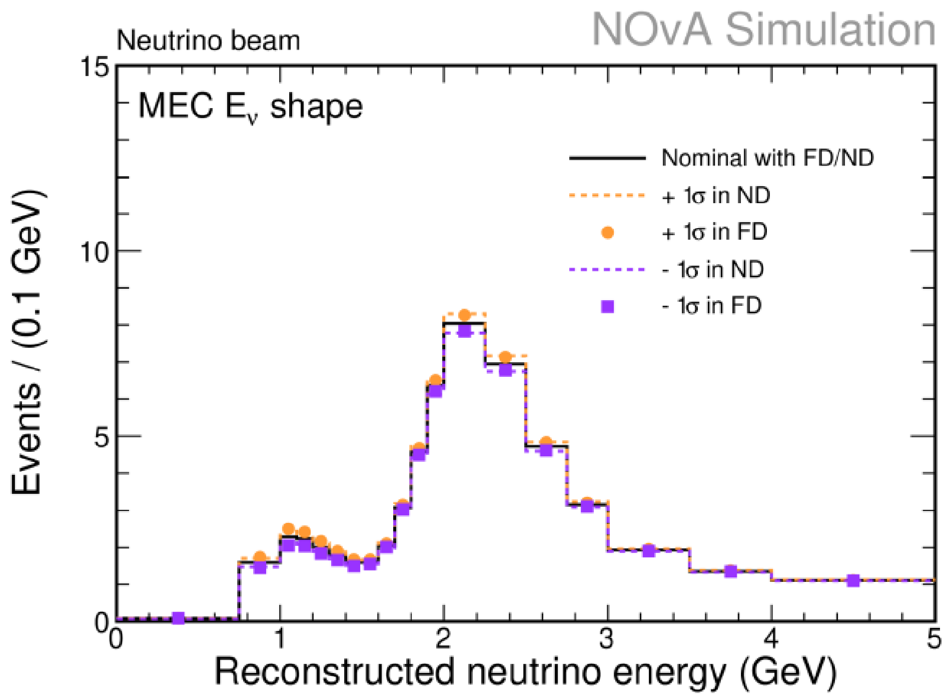


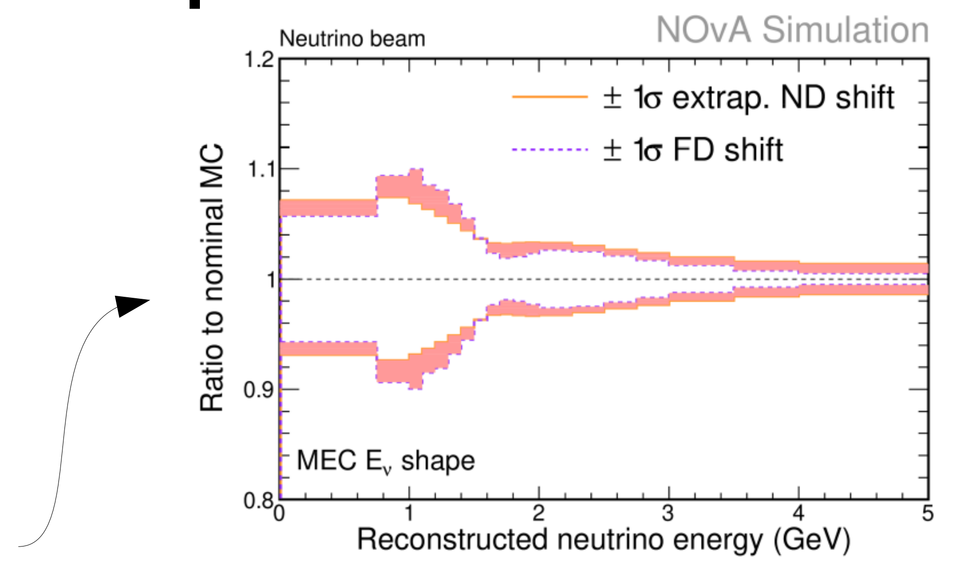


③ Compare "extrapolated" FD prediction to prediction obtained by varying FD directly.

If they match, extrapolation perfectly 'cancels' the effect.

Testing extrapolation





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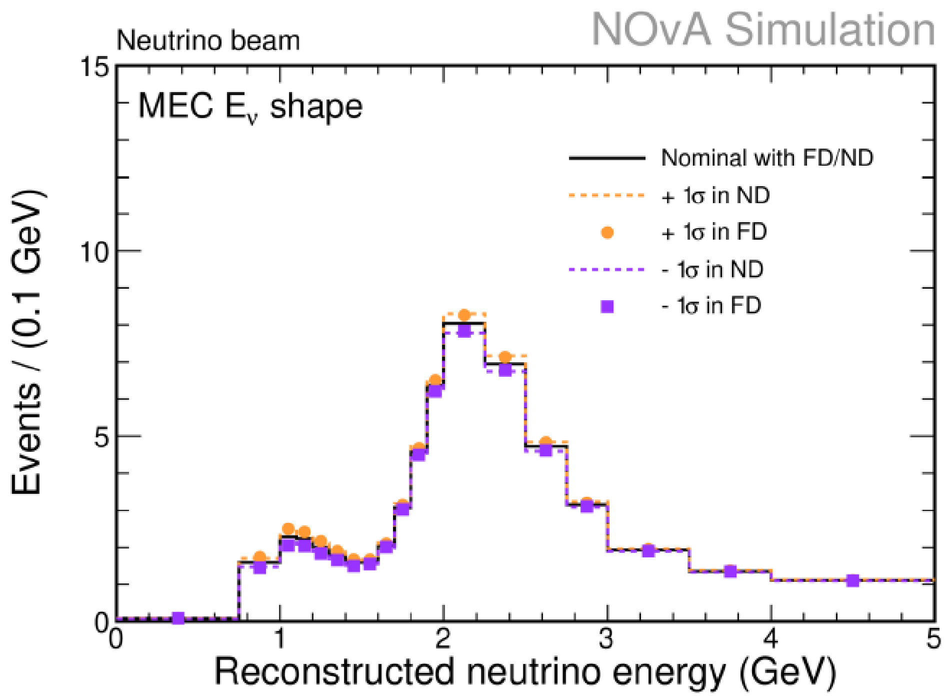
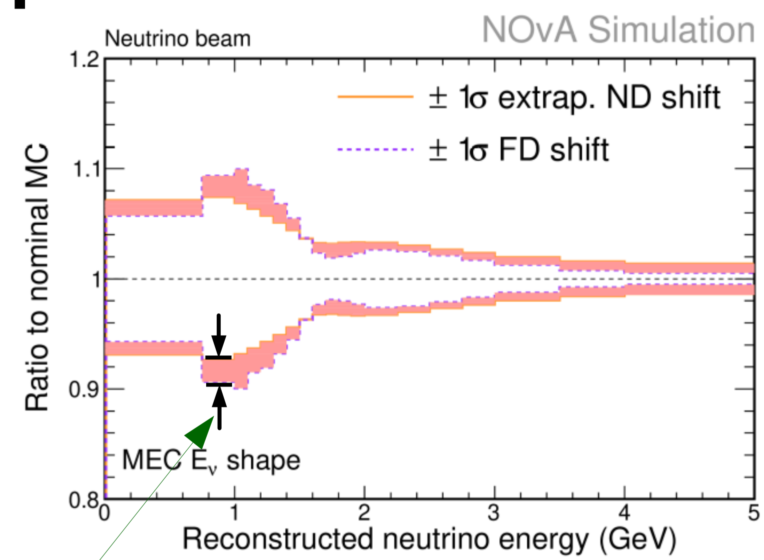
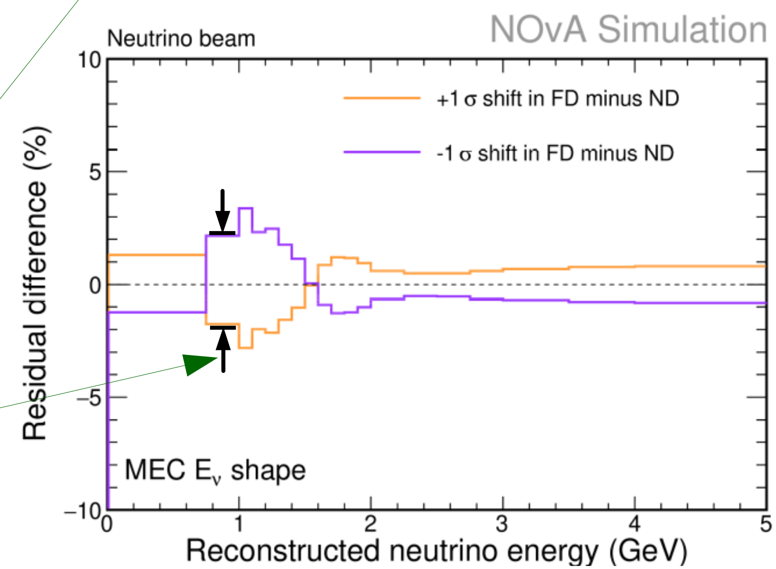
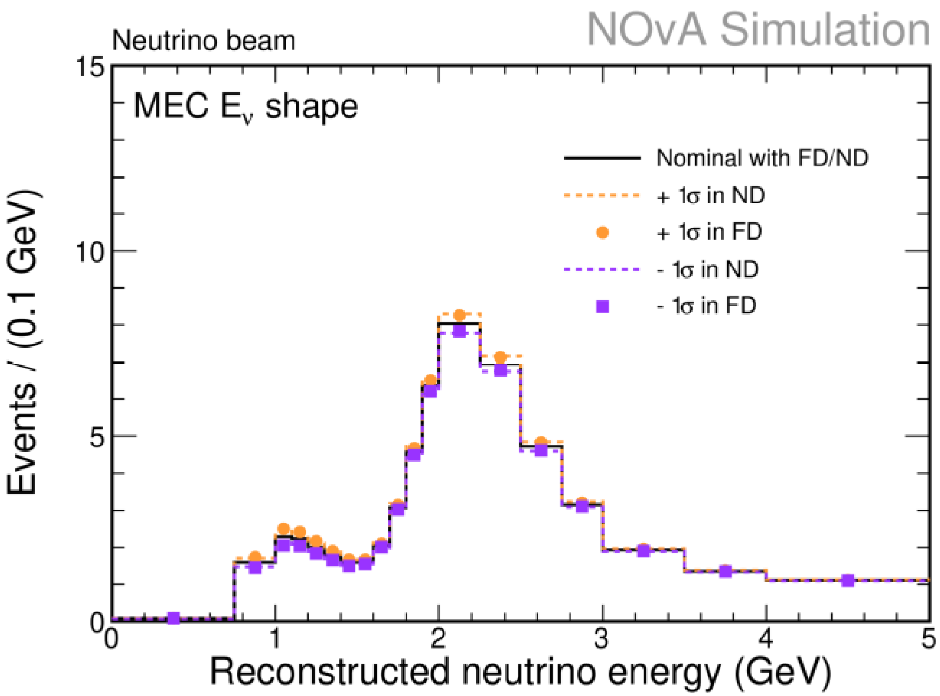


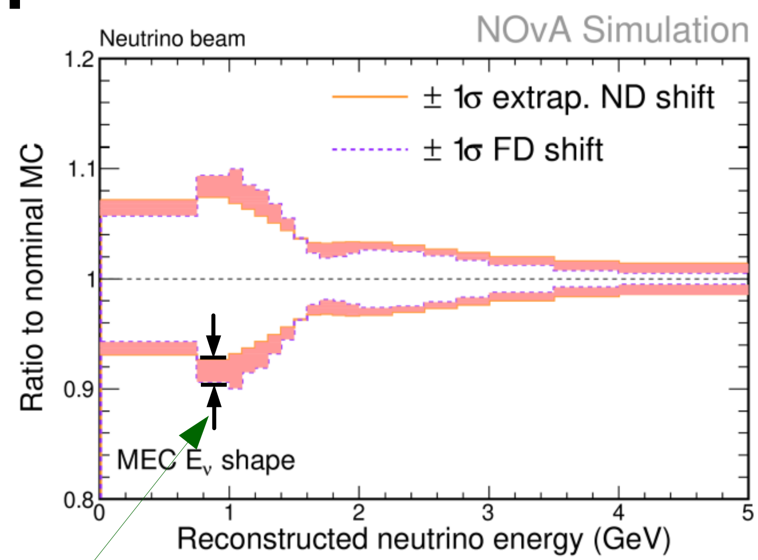


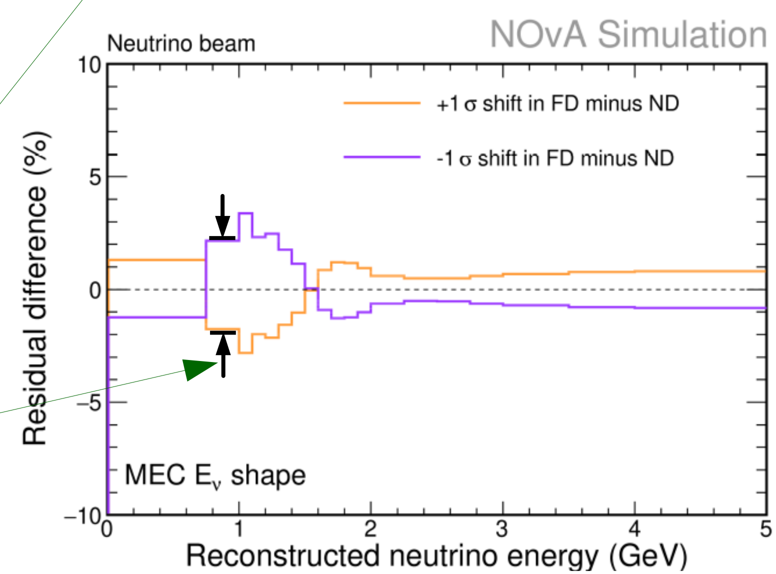


Only a few percent *residual* effect of this MEC syst after extrapolation: the rest was canceled by the procedure.

Testing extrapolation



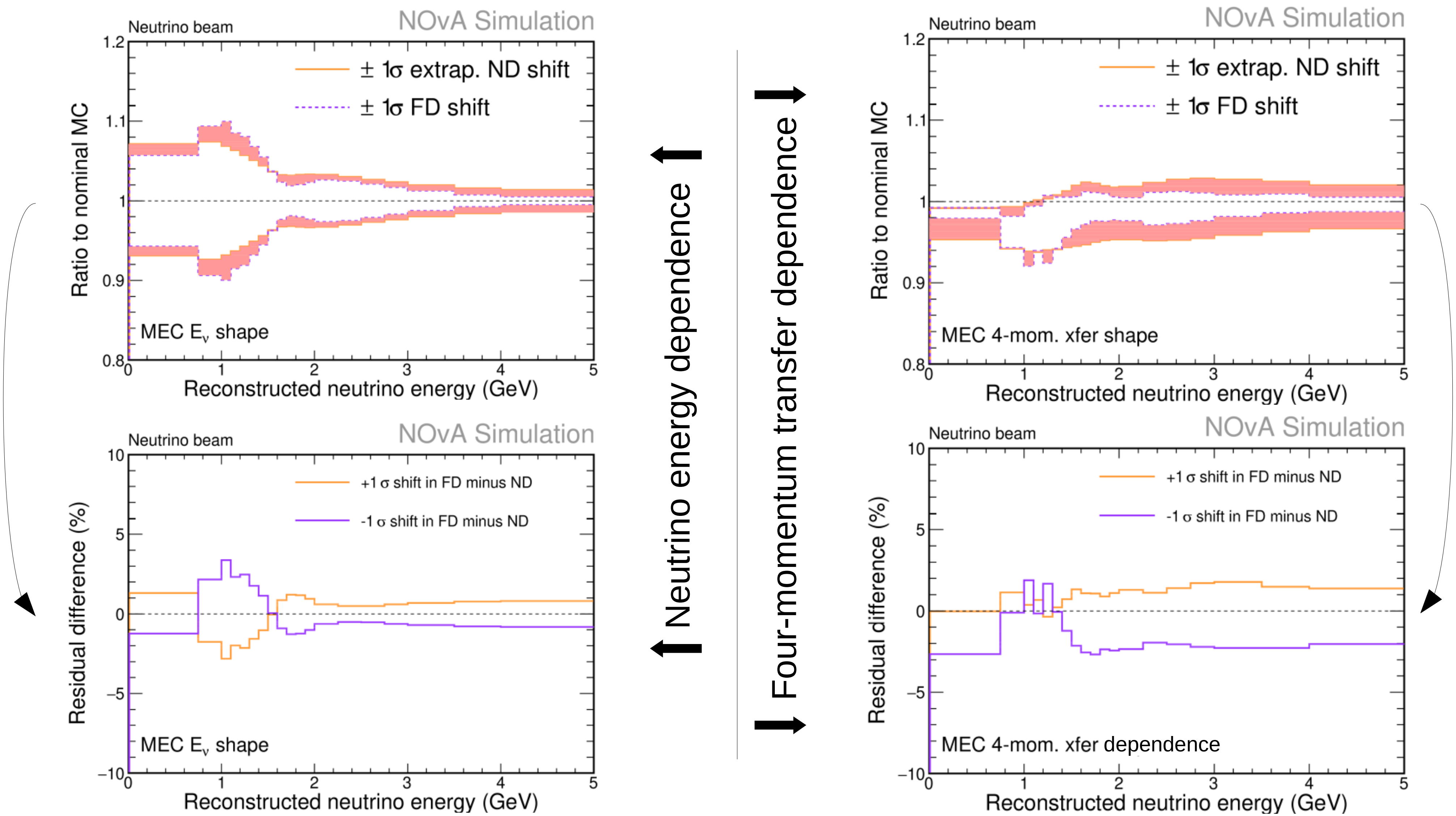




Only a few percent *residual* effect of this MEC syst after extrapolation

Though extrapolation procedure can't remove *all* effect of cross section uncertainties like MEC,
extrapolation significantly reduces sensitivity to XS systs

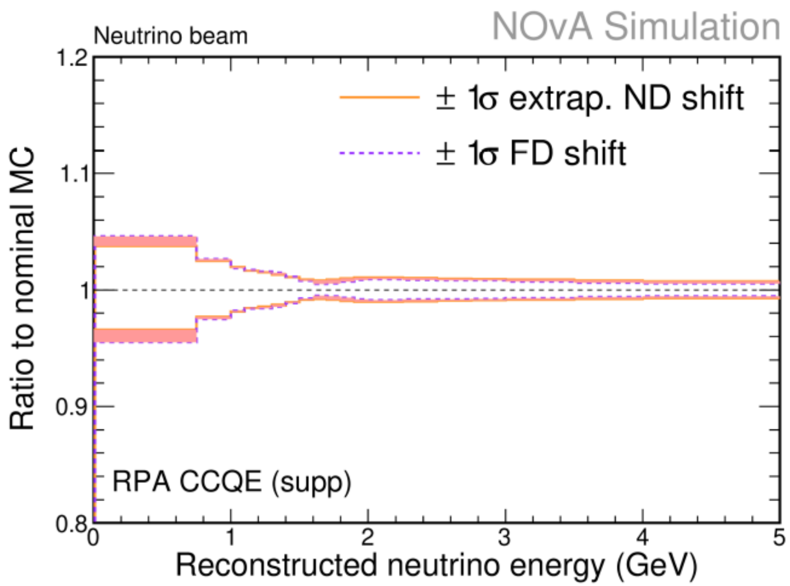
Testing extrapolation

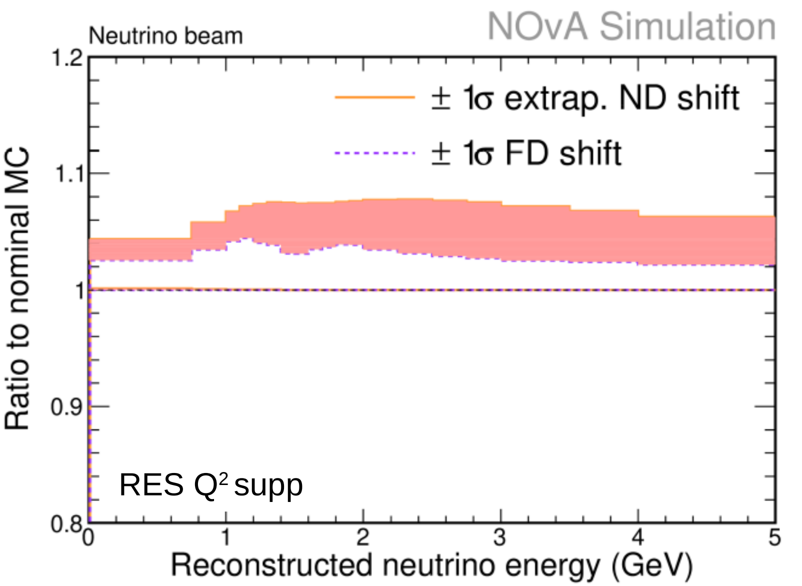


Far/Near extrapolation works best with *neutrino energy* systs,
but we derive benefit from it for the other shape dependence as well

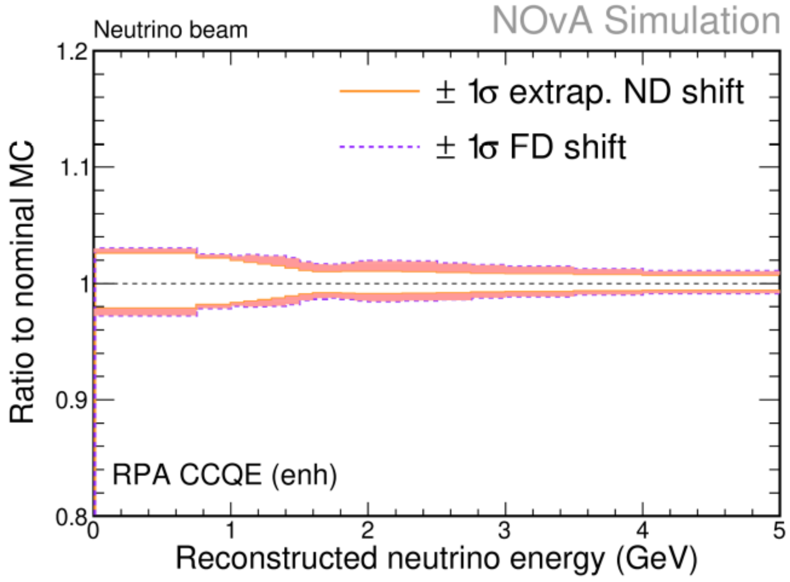
New since 2017

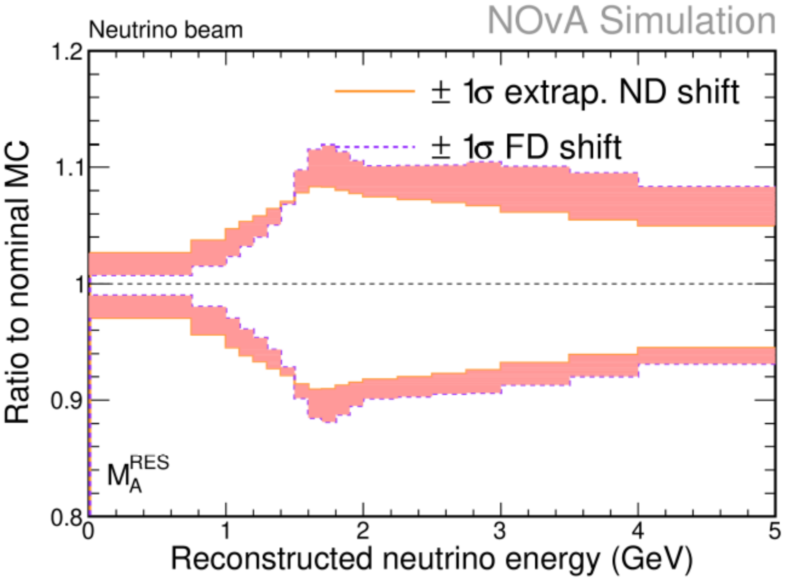
Other important XS uncertainties



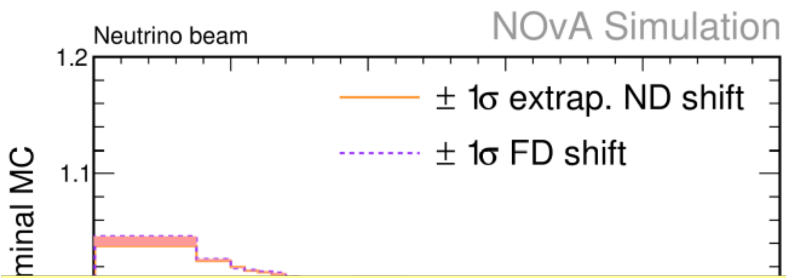


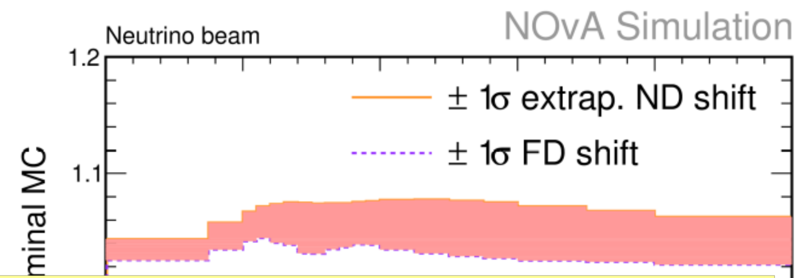
The story is similar for other important cross section uncertainties





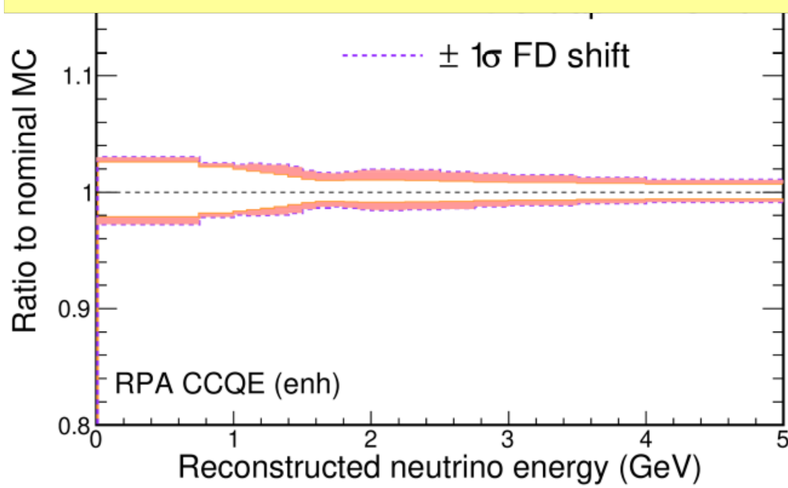
Other important XS uncertainties

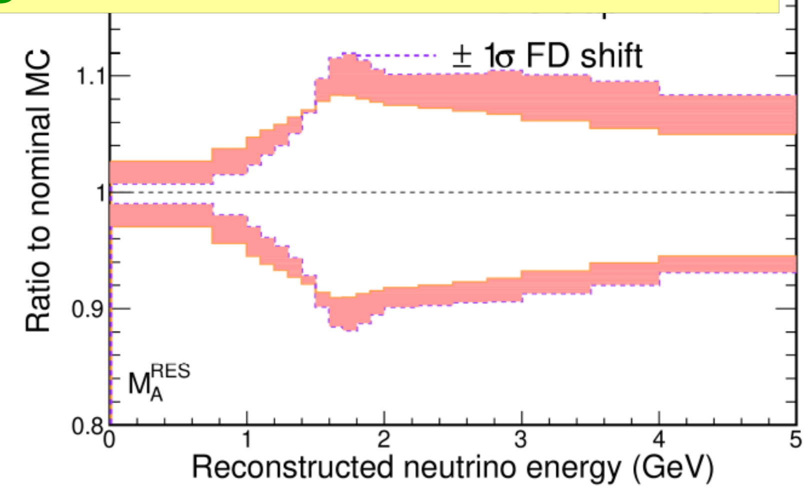




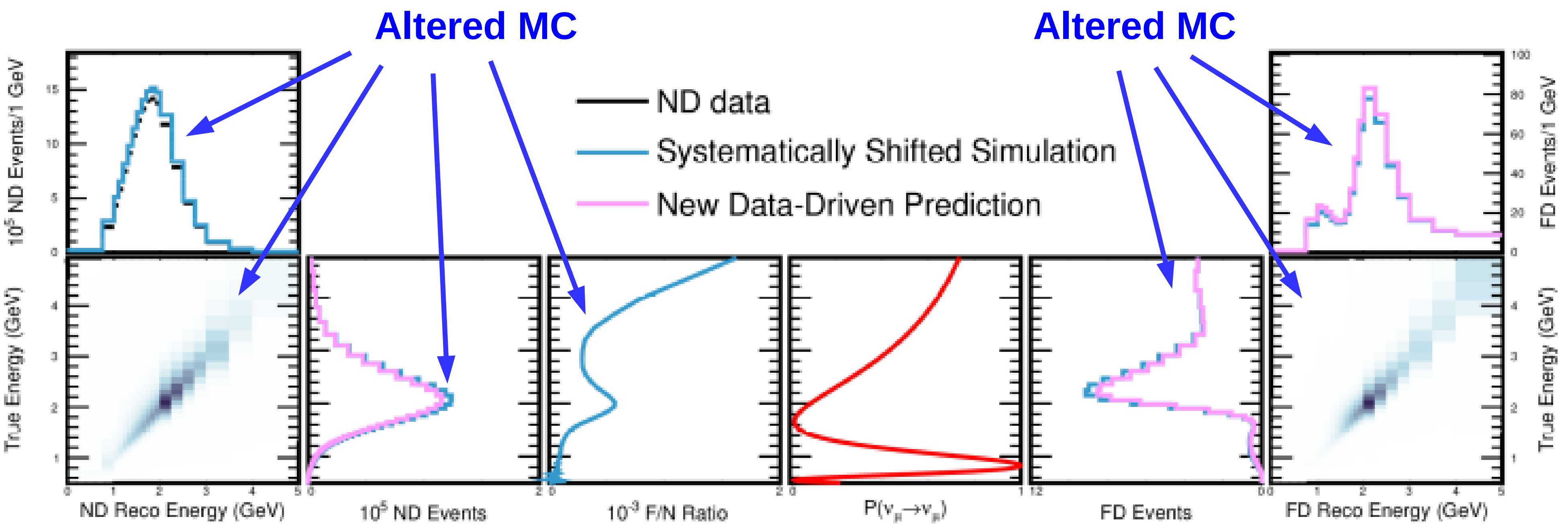
This illustrates how extrapolation responds to
“unknown unknowns” in the *data*.

We do the “inverse” to handle
“known unknowns” using our MC...





“Extrapolation” and uncertainties



We simulate the effect of our cross section systematics' *residual* effect after extrapolation

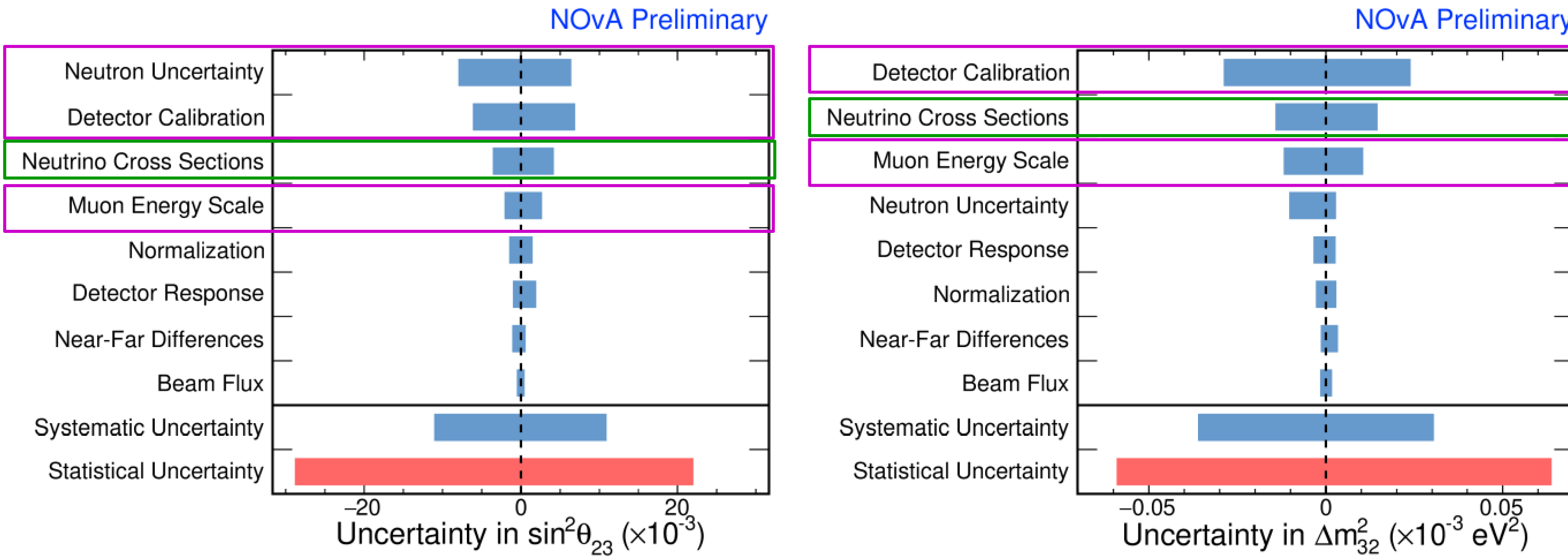
by re-doing the entire analysis for each systematic

(each of which can affect multiple both signal & bknd)

and use the difference to extrapolated nominal MC as nuisance parameters in our oscillation fits

2018 analysis

Effect on analysis



(Uncertainty on joint $\nu + \bar{\nu}$, $\nu_\mu + \nu_e$ fit)

Cross section systematics are not dominant systematic uncertainties due to detector design & power of extrapolation.

But... dedicated **test beam program** (data taking in 2019) will likely drive detector response uncertainty down in the future, so soon enough cross sections will likely be atop the list...

Now:

ν_e appearance

ν_e appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$

$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

$$+ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

Where: $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \quad \Delta = \Delta m^2_{31} \frac{L}{4E} \quad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$

Besides the dependence on the mixing parameters, we learn about the mass ordering (via α) and δ_{CP}...

ν_e appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$

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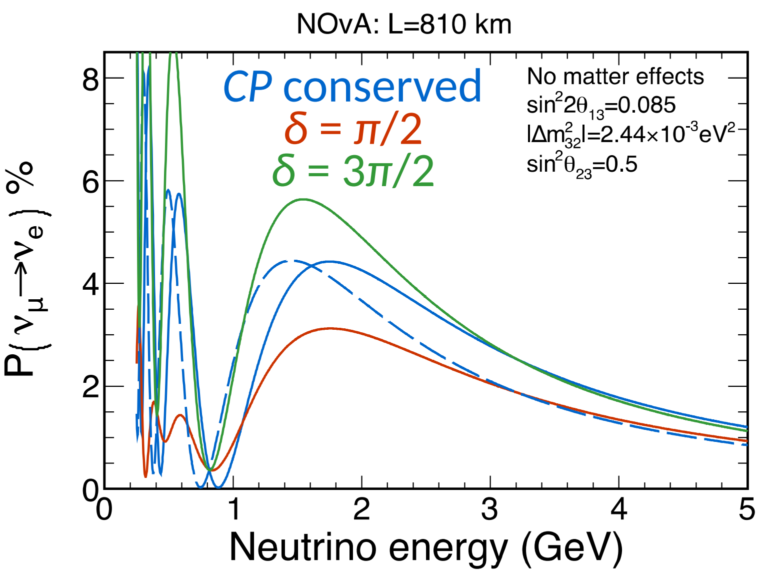
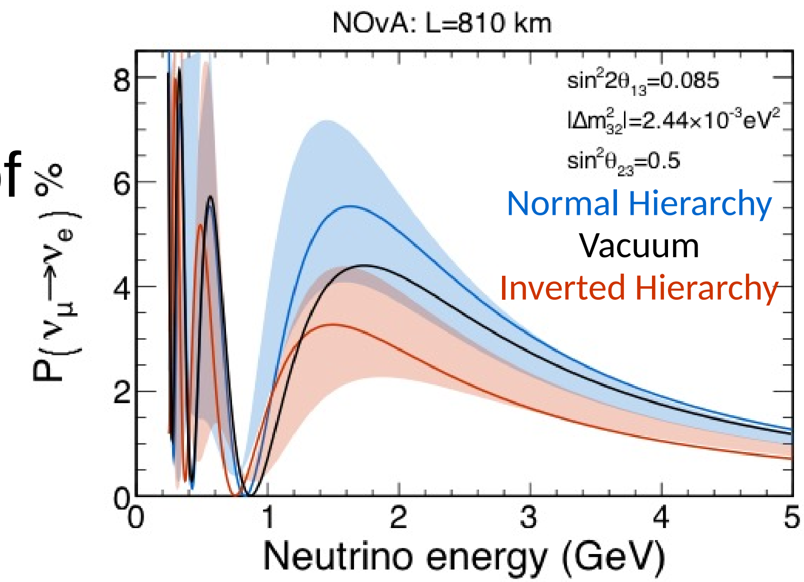
Besides the dependence on the mixing parameters, we learn about the mass ordering (via α) and δ_{CP}...

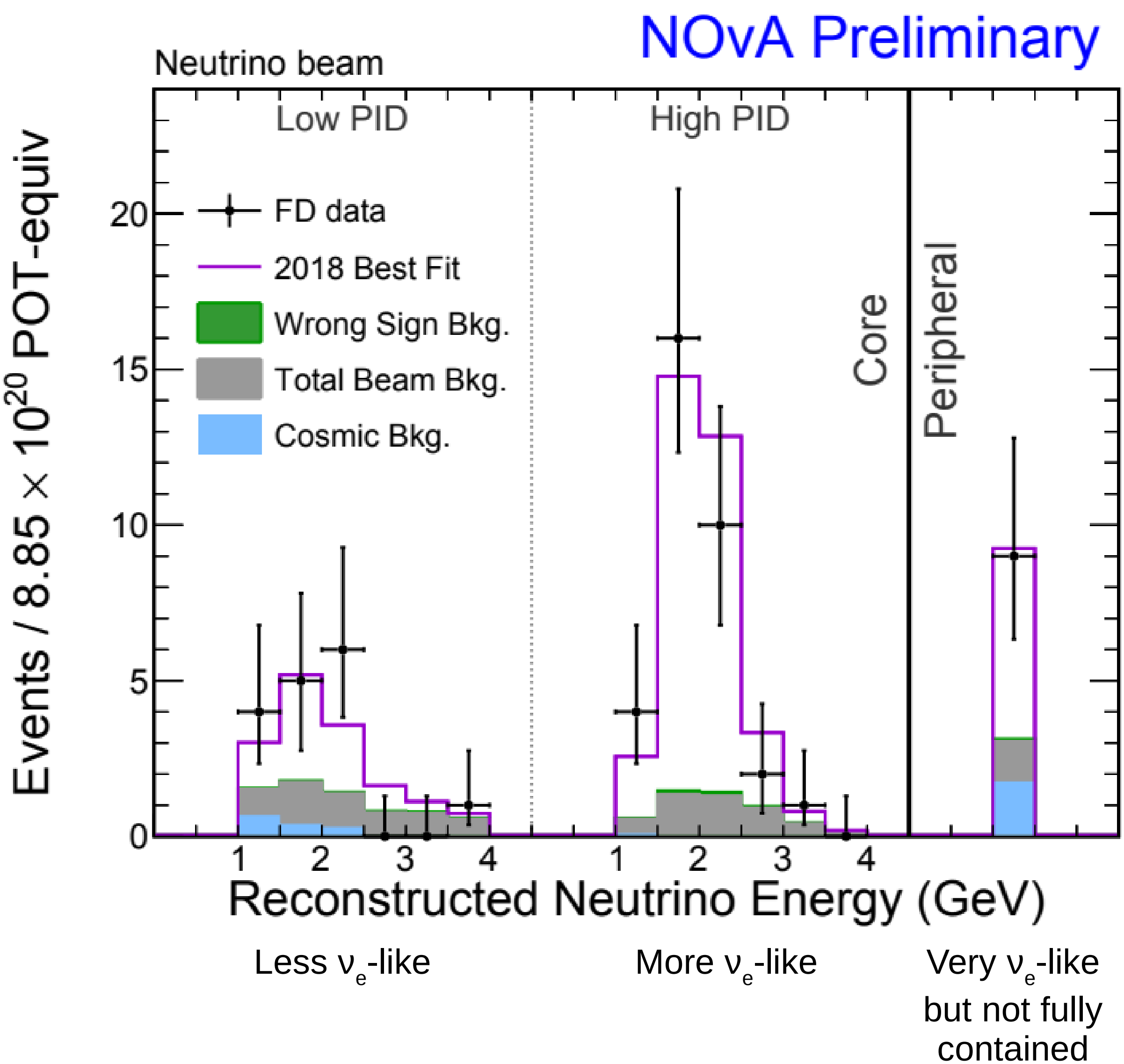


...but smallness of θ_{13} makes it a very challenging measurement



2018 analysis

ν_e appearance

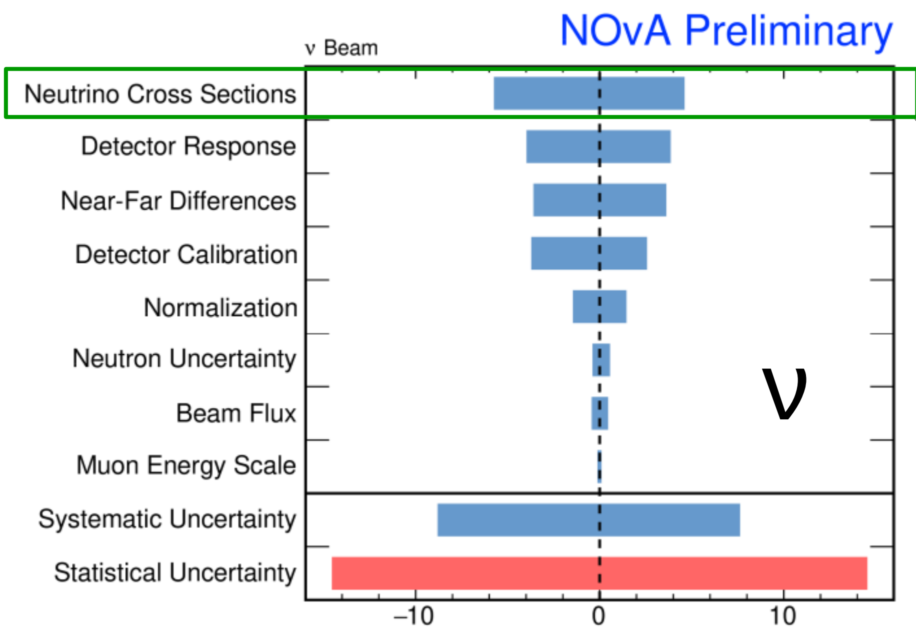


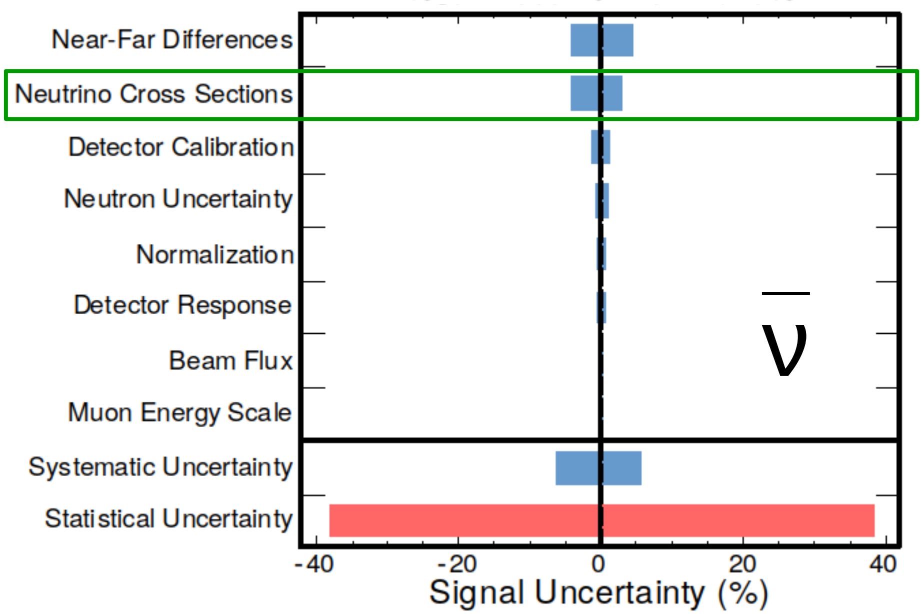
Added challenges:

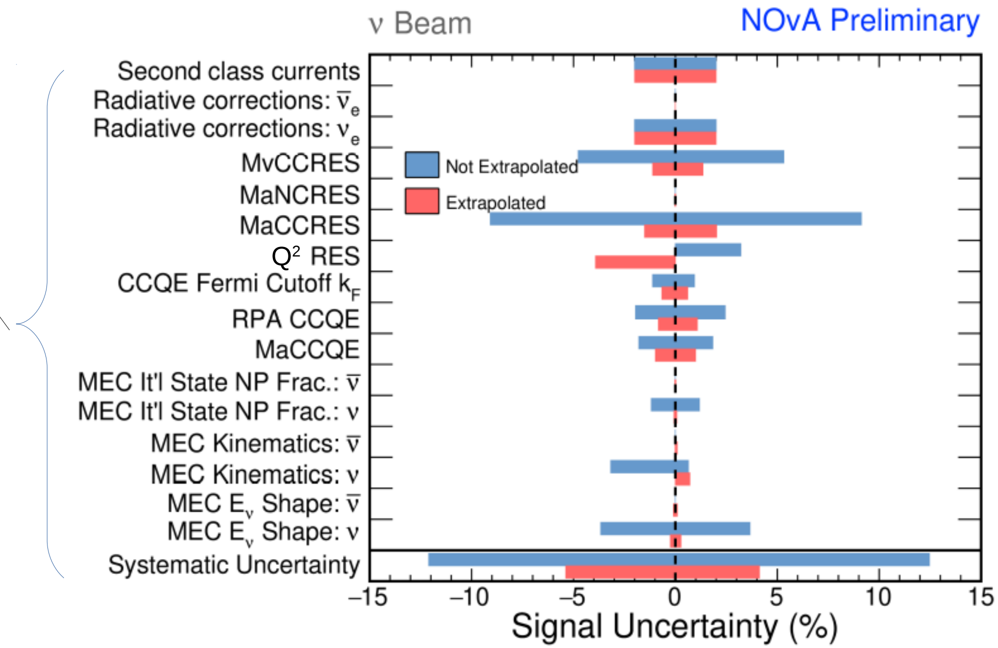
- **No signal at ND**
  - Need to assume relationship between ν_μ and ν_e XSs
  - Different acceptance, ν_μ ND vs. ν_e FD
- **Nontrivial beam backgrounds which oscillate differently**
  - **Beam ν_e** oscillate very little over this L/E
  - **ν_μ** almost entirely disappear
  - **NC** doesn't change due to oscillations (assume no steriles)

(Need to disentangle ["decompose"] before applying Far/Near makes any sense.)

ν_e appearance







Cross section systematics still under control for now, but can't help ν_e/ν_μ diff with ND...
(Even more stat limited for $\bar{\nu}$.)

We expect to continue to benefit from ongoing work by this audience as well to keep them that way...

Cross section uncertainties: future needs

- **Refinement of 1p1h initial state prediction**
  - Unified nuclear model treatment in GENIE (move past RFG+RPA?)
  - Study binding/separation/removal energy situation (A. Bodek, arXiv:1801.07975)...
- **More/better models for multinucleon knockout in GENIE**
  - Need theory models that describe inclusive data at E_ν > 1 GeV. SuSA-MEC in GENIE soon?
  - Need to study effect of anisotropic ejection of nucleon pairs
- **Nuclear models for *inelastic* processes**
  - Examine alternatives to GENIE hA FSI
  - What's causing low-Q^2 suppression? (“On-off” syst one of our largest)
- **ν_e/ν_μ for inelastic processes**
- **More antineutrino data**
- **...**

Summary

- NOvA relies on **strong internal constraints** on cross section uncertainties for its oscillation program
  - Calorimeter design minimizes *a priori* impact
  - Functionally identical detectors enable major cancellation of residual errors in oscillation analyses
- Comprehensive program underway to ensure all **relevant cross section issues are considered**
  - Necessary ingredients in base model
  - Appropriate uncertainties
- We look forward to **continuing the conversation**:
  - Continued development of models & systematic treatments
  - New measurements of cross sections
  - Neutrino oscillation physics results!

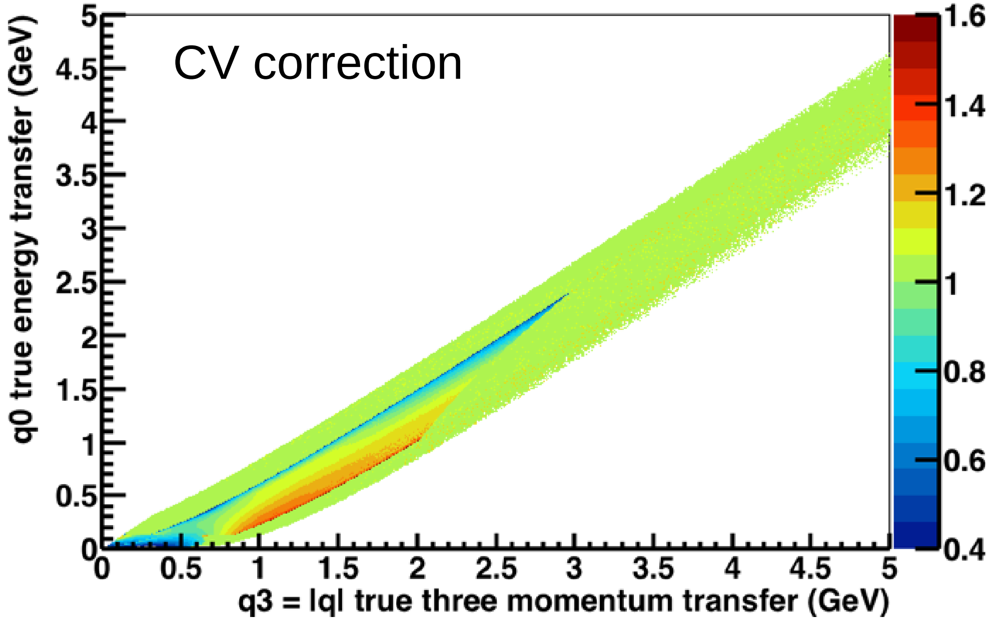
[NOvA 2018 at University of Austin]

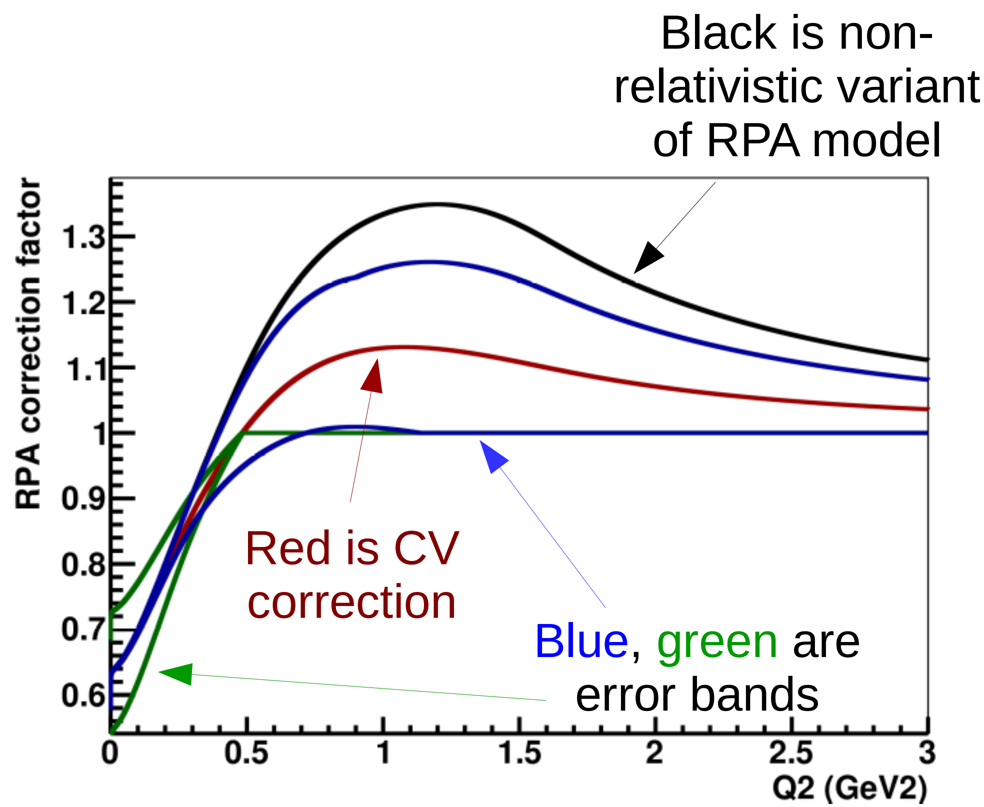
Thank you for your attention!

Overflow

Modeling the nucleus: collective effects (RPA)

[R. Gran, arXiv:1705.02932;]



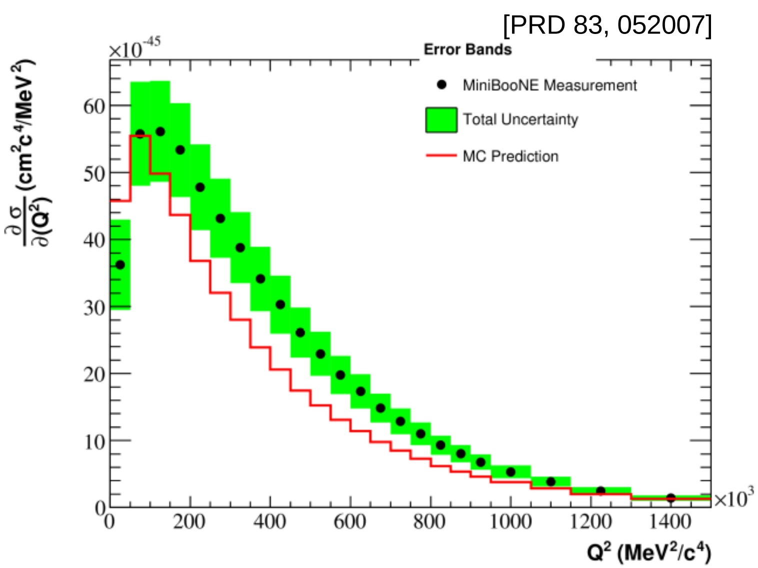


Rik Gran's work (originally for MINERvA) to extend the València RPA CCQE effect (PRC 70, 055503) to a correction for GENIE's central value and his work to extend the uncertainties in the model to higher energies (PLB 638, 325, PRD 88, 113007) naturally work reasonably well for NOvA

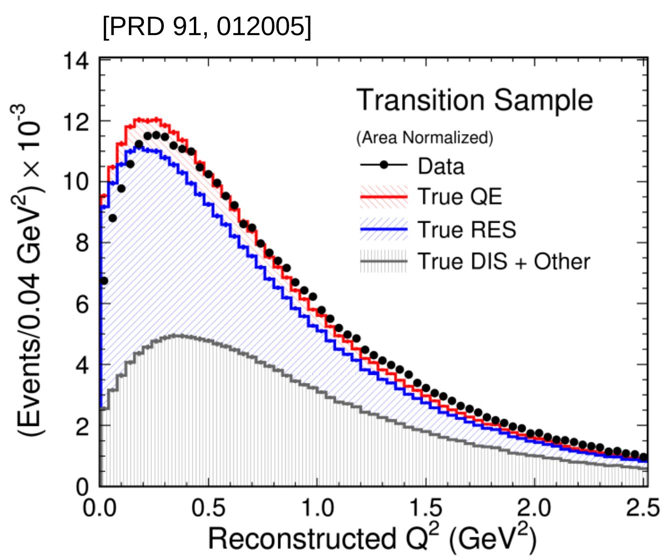
→ we apply using Rik's code

Modeling the nucleus: collective effects (RPA)

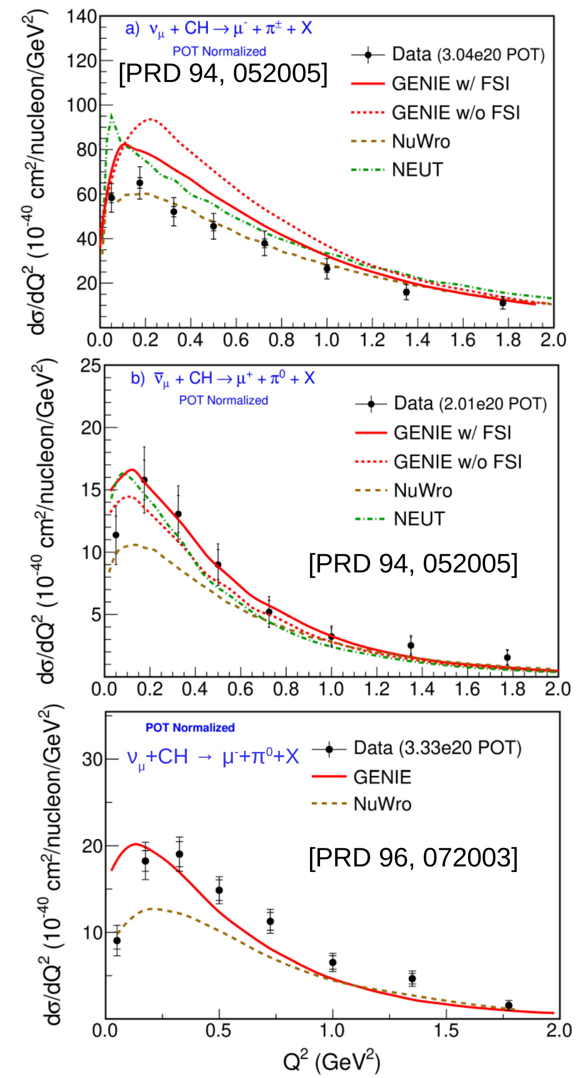
- Should Δ production also be affected?
  - Energy transfers are large (>100 MeV), so perhaps not "traditional" RPA...
  - But suppression at low Q^2 appears in many data sets: MiniBooNE, MINOS, MINERvA



MiniBooNE 1π+



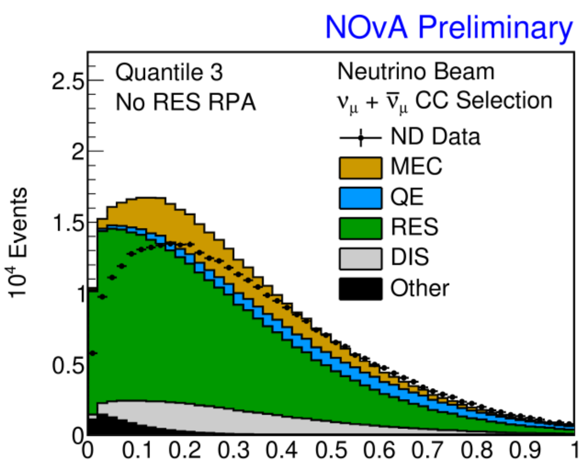
Sideband, MINOS QE

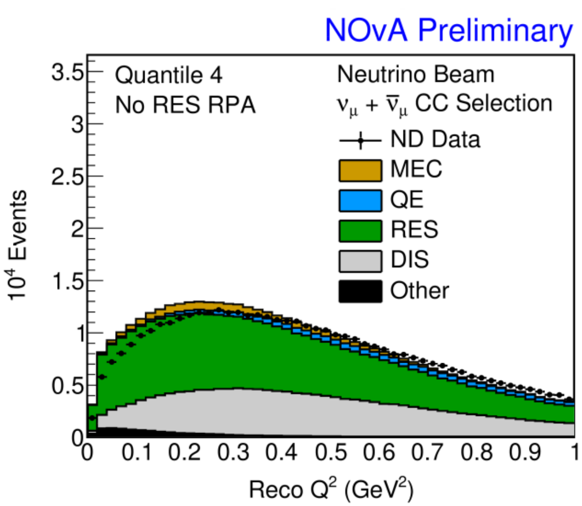


MINERvA

Modeling the nucleus: collective effects (RPA)

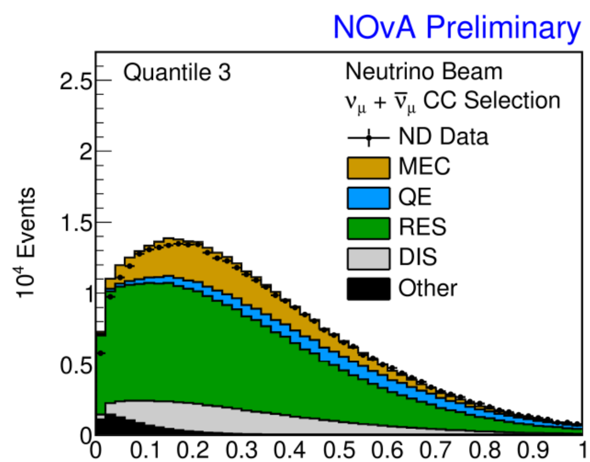
- Should Δ production also be affected?
  - Not surprising that *some* initial-state nuclear effects might influence resonances (relative to RFG)...

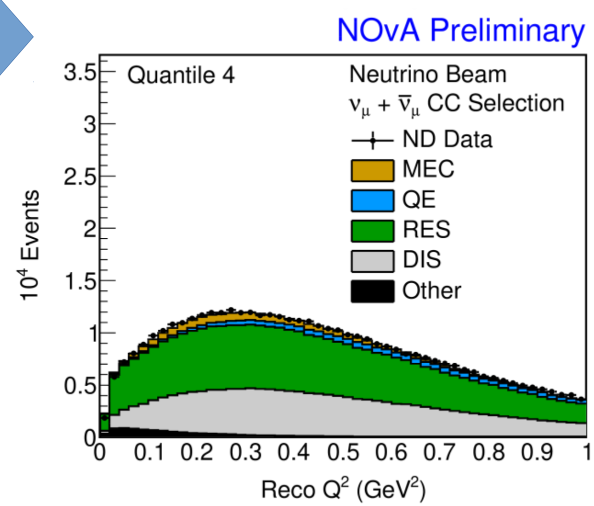




"Quantiles" are divided by hadronic energy fraction: reco E_{had}/reco E_ν.

Quantiles 3 & 4 are RES-rich regions of ν_μ candidate sample.



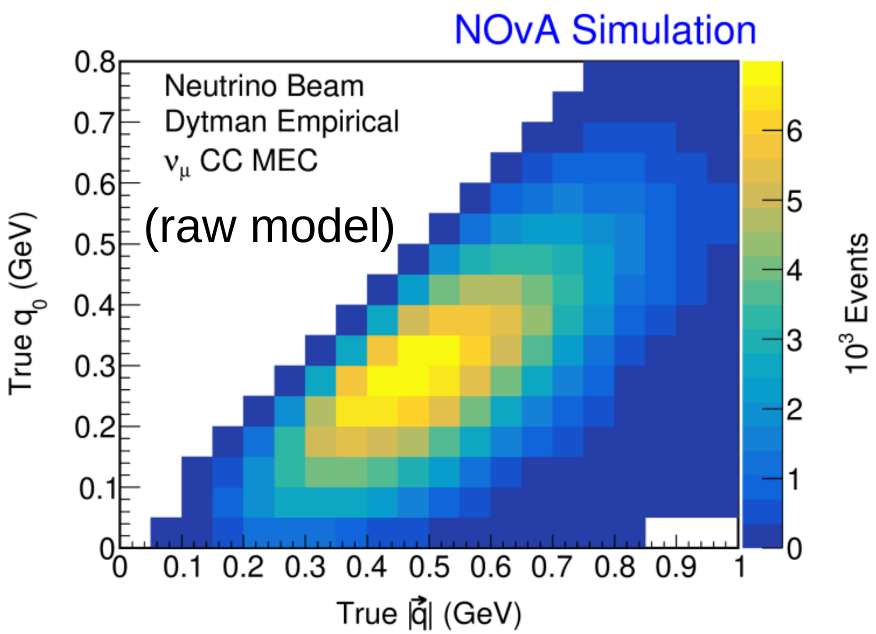


We apply the Q^2-based RPA weight from QE to resonant production as a stand-in for whatever nuclear effect it may be (w/ unmodified version as uncertainty variation)

Modeling the nucleus: tuning 2p2h-MEC

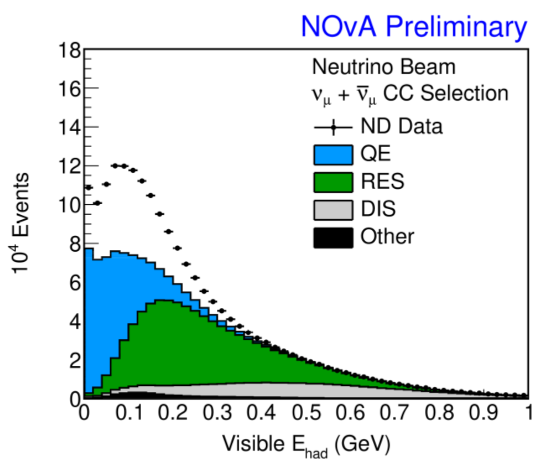
Our tuning is done in a two-dimensional space of the four-momentum transfer variables:

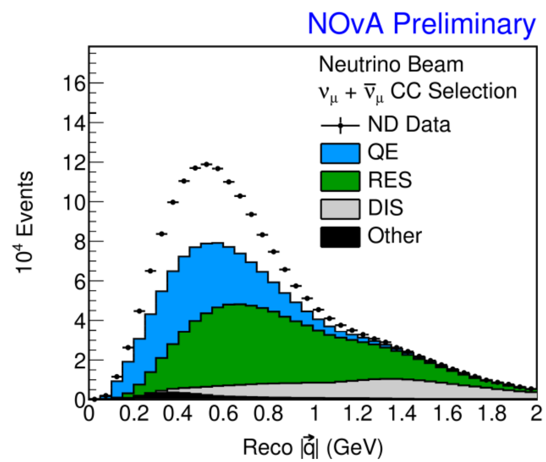
energy transfer q_0
and
momentum transfer |q|

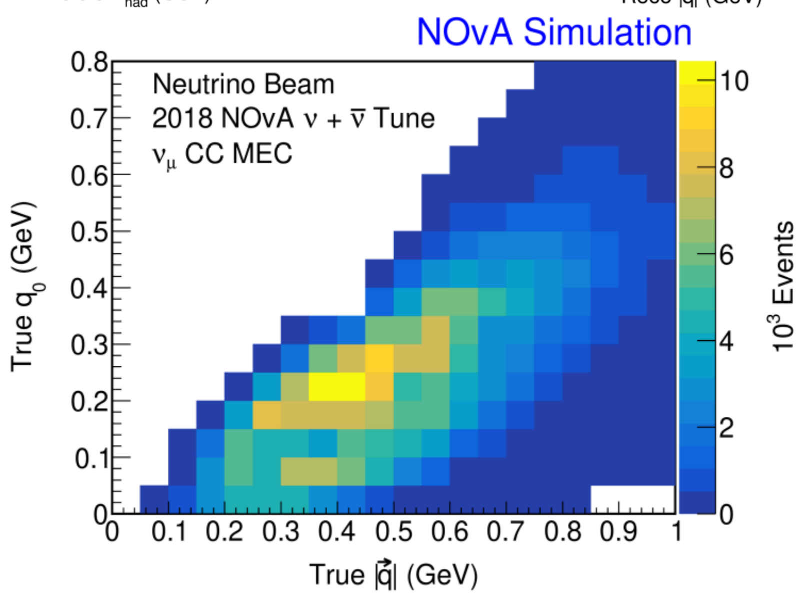


fit a weight factor for each cell in this plot

Fit in 2D space of nearest observables: Visible E_{had} (~q_0) and reco |**q**|

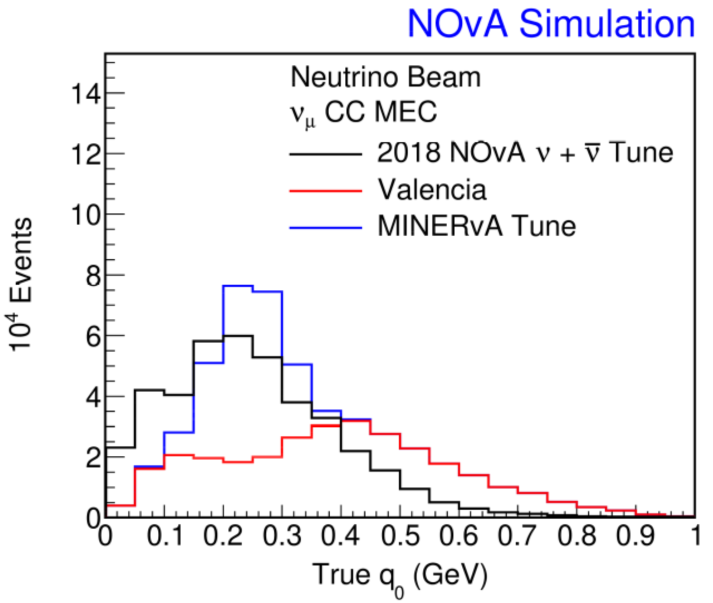


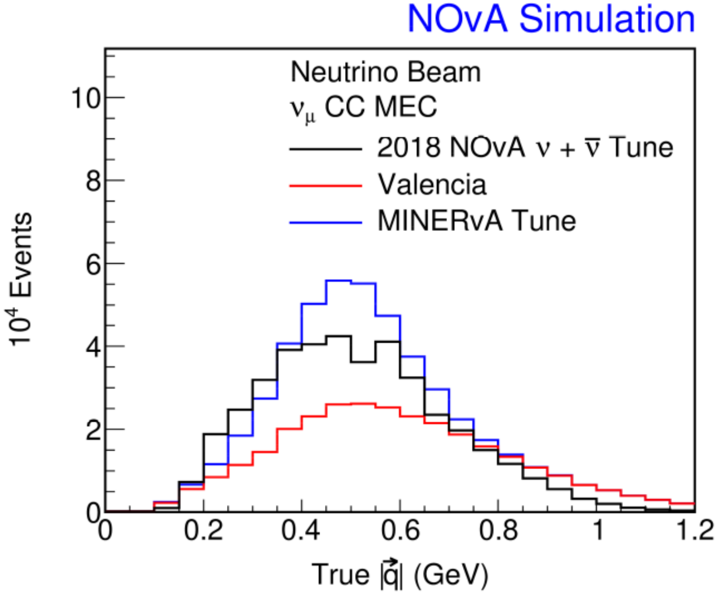




Resulting MEC shape

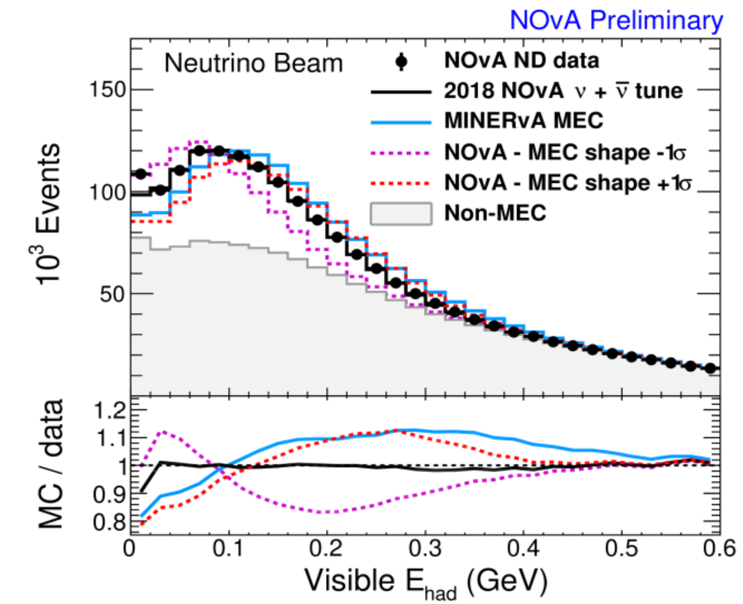
Modeling the nucleus: tuning 2p2h-MEC

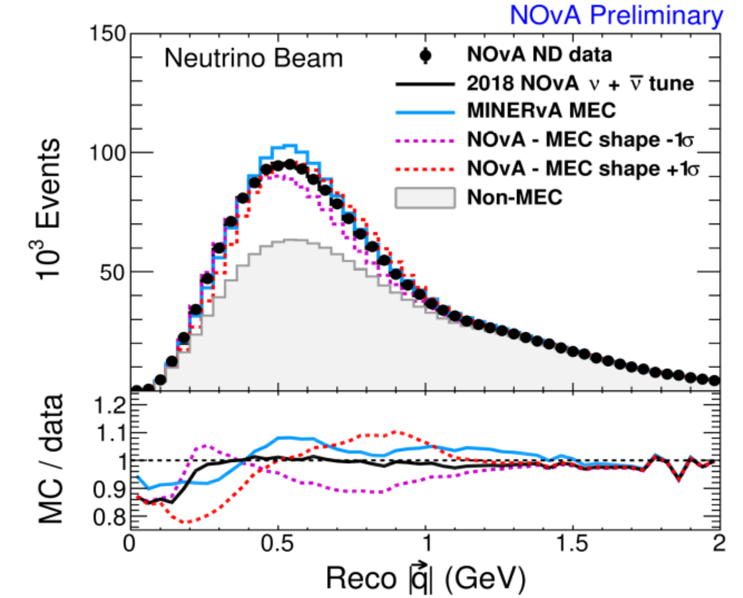




MINERvA carried out a tuning procedure similar in spirit to ours (though with fewer degrees of freedom) using their data (PRD 116, 071802) which they kindly shared with us (private communication).

It is not dissimilar to the 1σ error band we arrive at (details on error construction next slide)





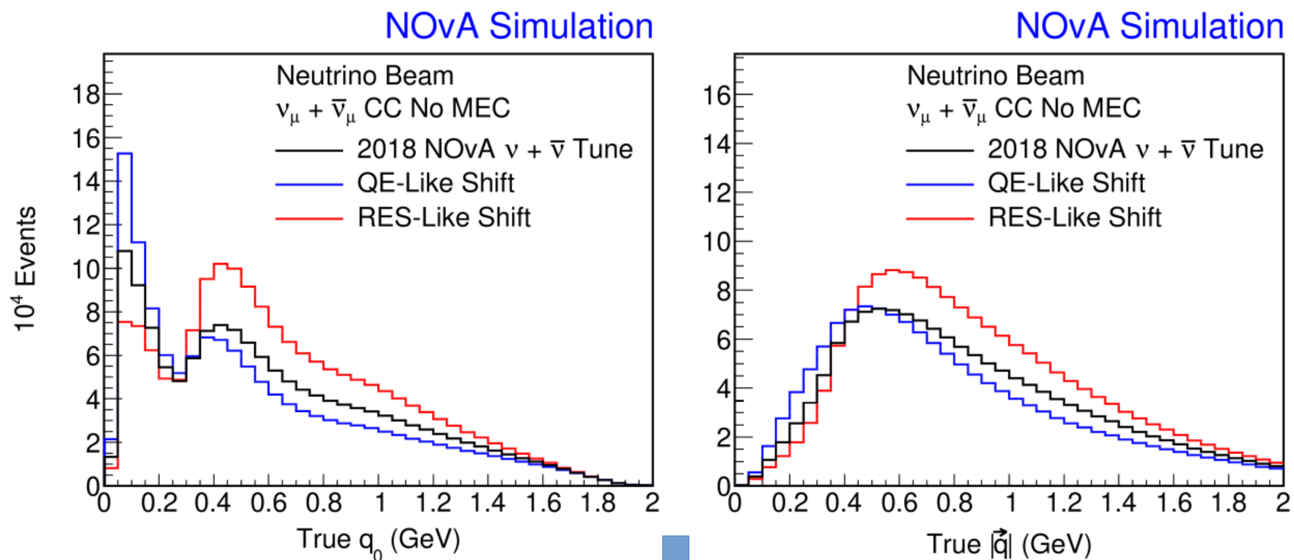
Modeling the nucleus: 2p2h-MEC uncertainties

Two alternate fits:

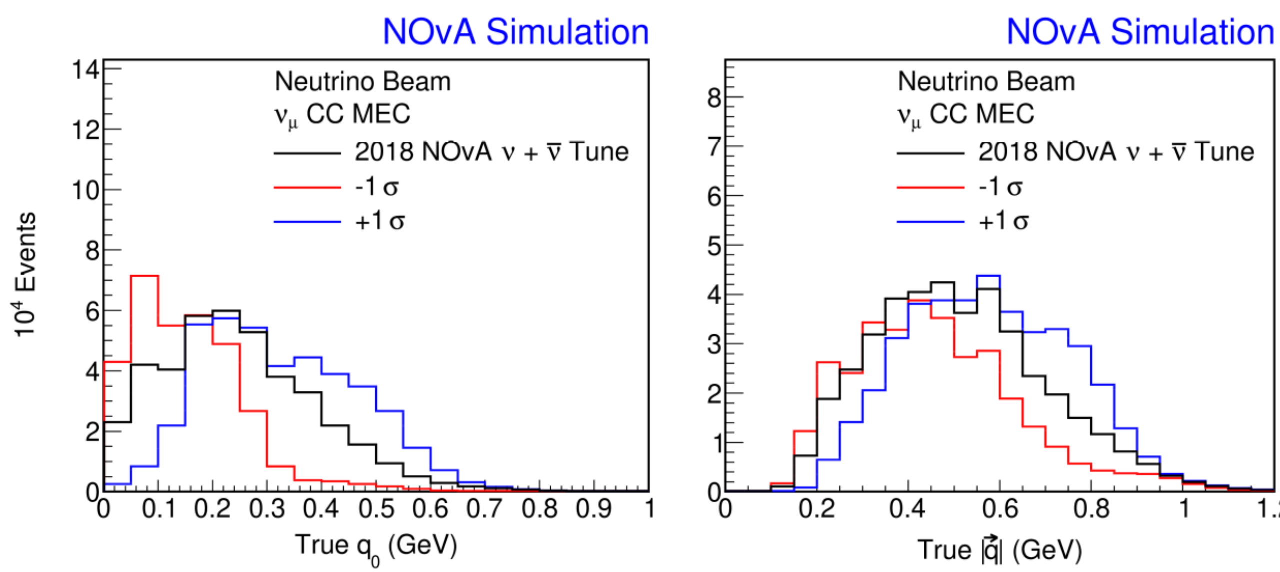
Choose combinations of uncertainties to push initial MC more towards QE or RES

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

Non-MEC base

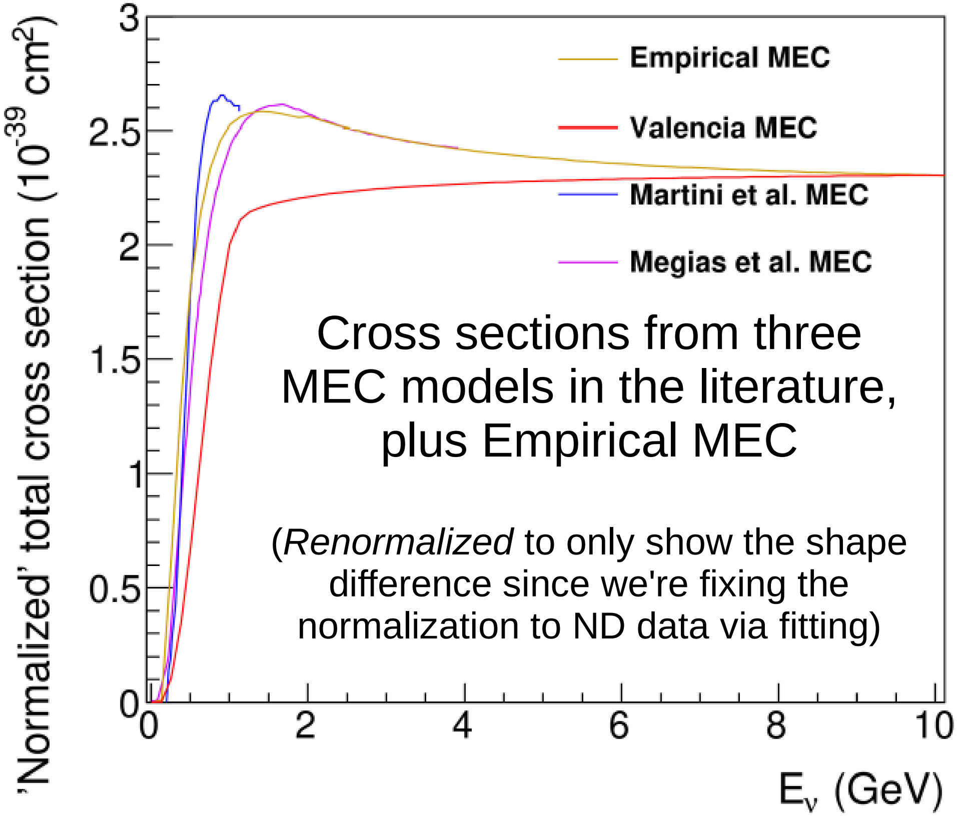


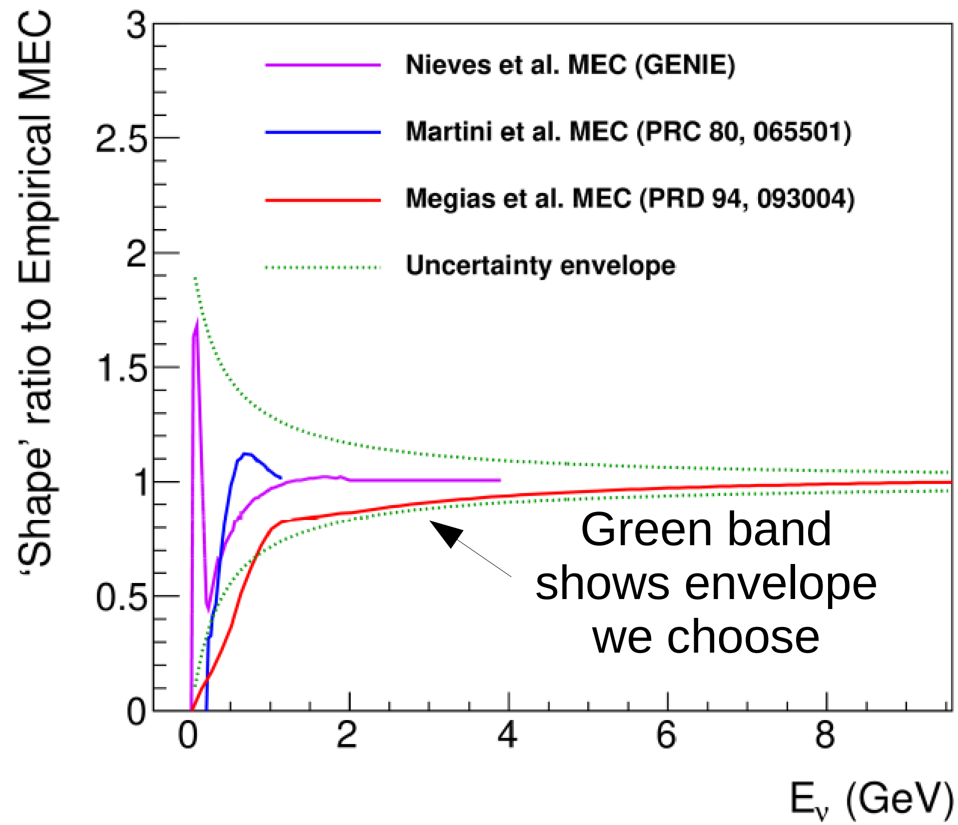
Fitted MEC



Modeling the nucleus:
2p2h-MEC uncertainties

Cross section E_ν shape



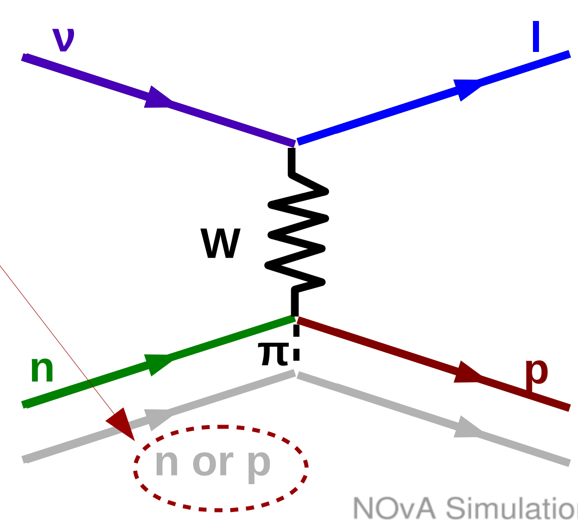


Choose an envelope that more or less encloses the shapes of the predictions for our "±1σ" uncertainty

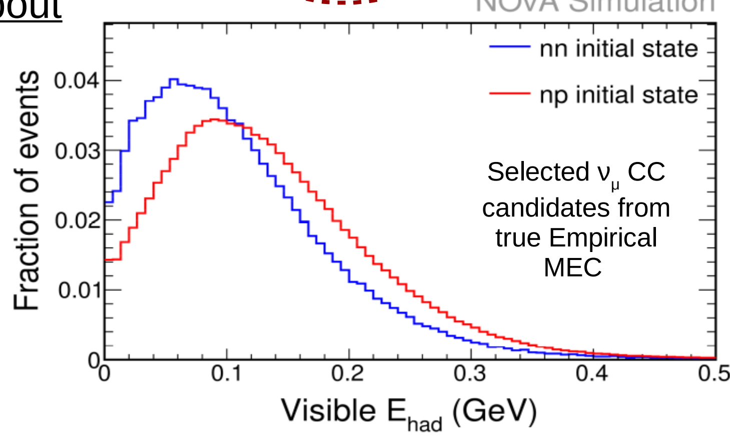
Modeling the nucleus: 2p2h-MEC uncertainties

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%

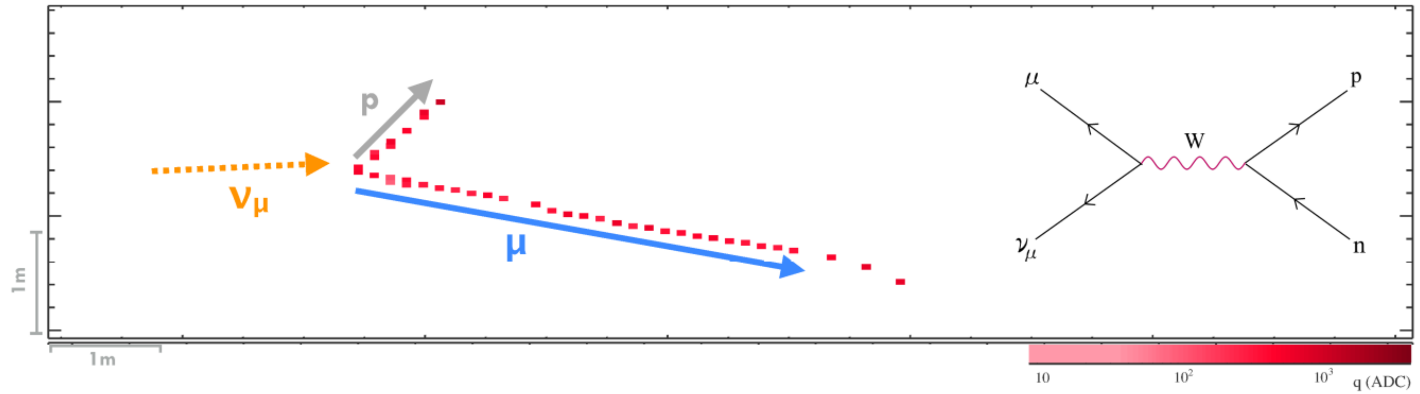


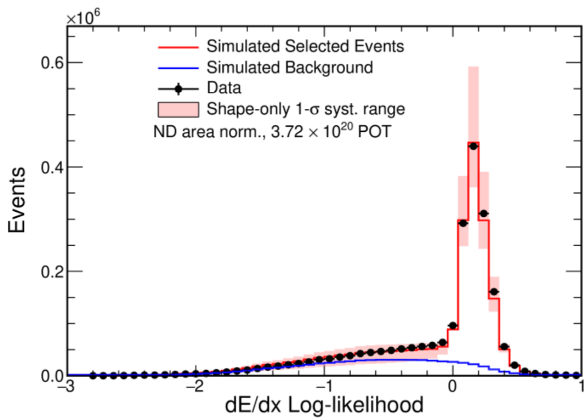
We choose $$0.7 \le \frac{np}{(np+nn)} \le 0.9$$ at 1σ.

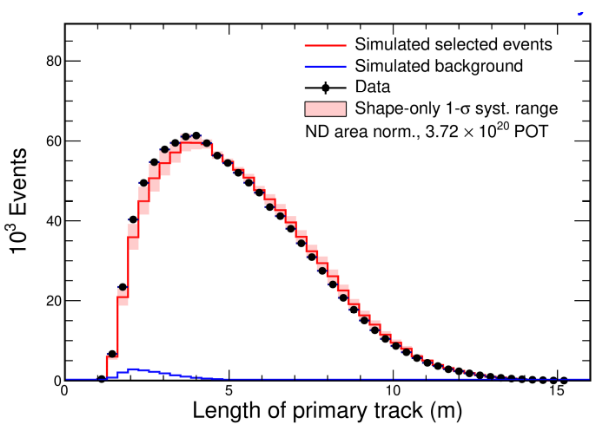


(It doesn't matter much; GEANT says we get ~similar response)

ν_μ disappearance: selection

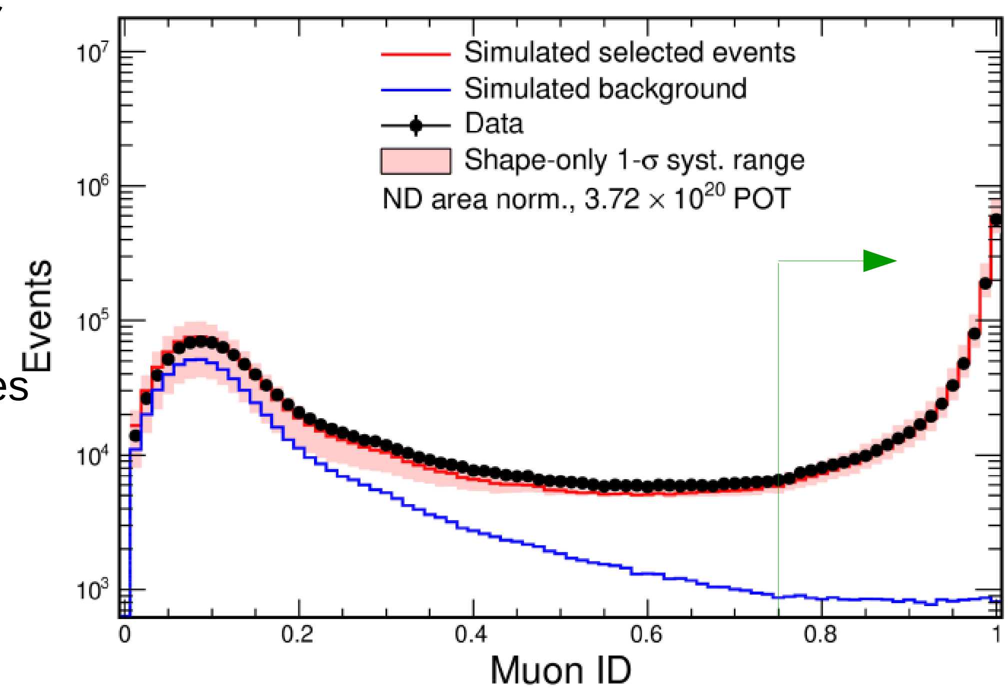






kNN-based ν_μ CC classifier uses
4 inputs:

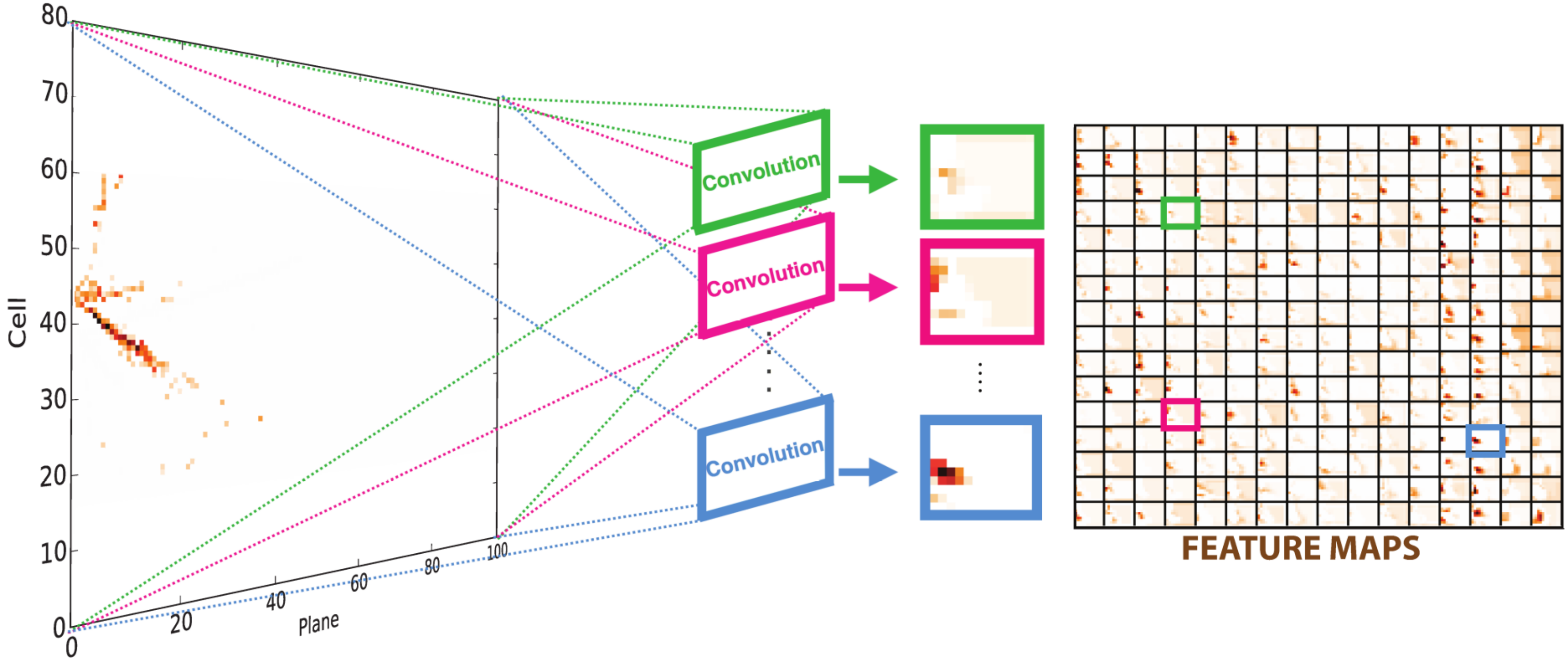
- Track length
- dE/dx
- Multiple scattering
- Fraction of track planes consistent w/ single particle dE/dx



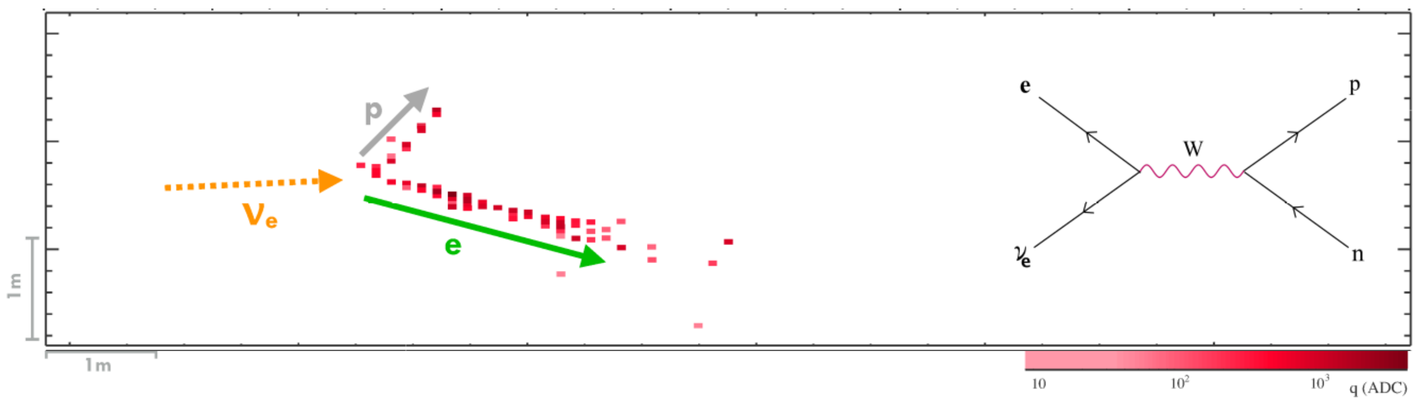
ν_e appearance: selection

Event selection via a "Convolutional Neural Network":

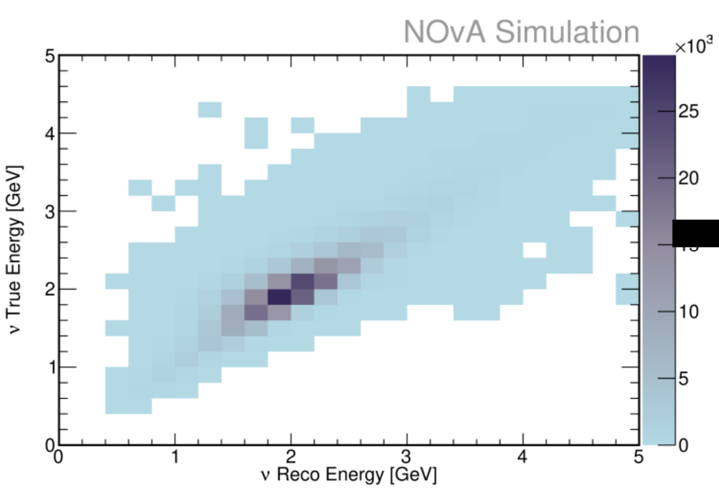
energy deposition patterns treated as images, algorithm extracts representative abstract features by applying learned filters

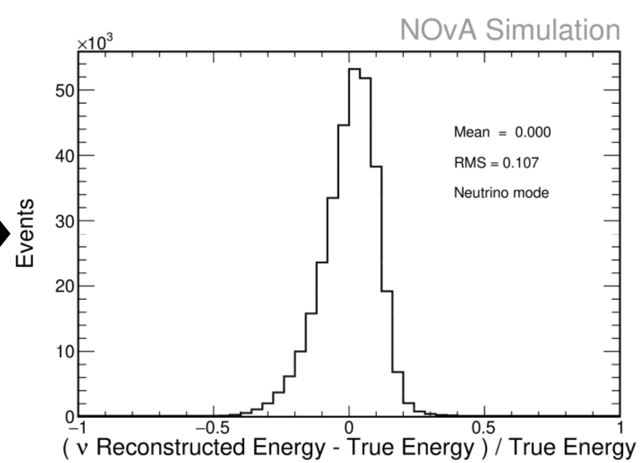


ν_e appearance: selection & reconstruction



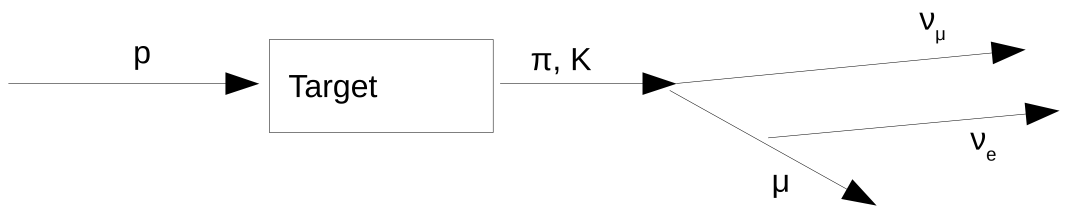
Convolutional neural network selects events via transformations applied to energy deposits treated as images

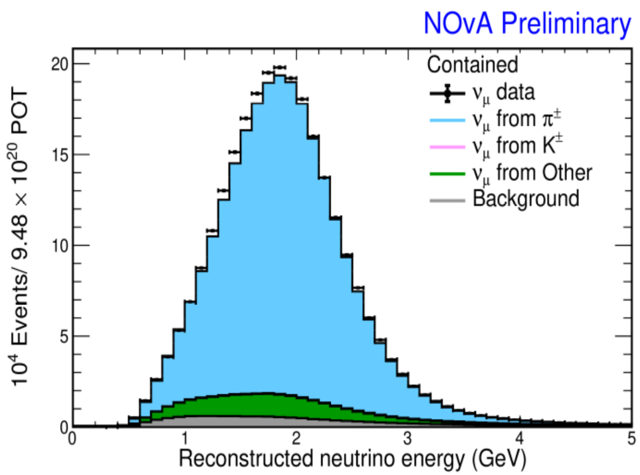


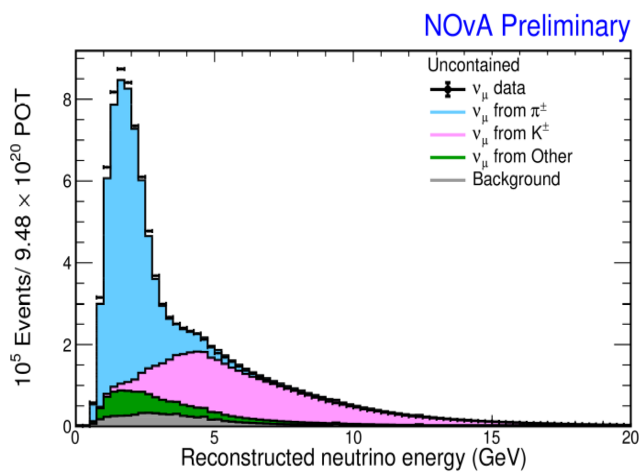


Energy estimator is quadratic function of E_e and E_{had}. ~11% resolution

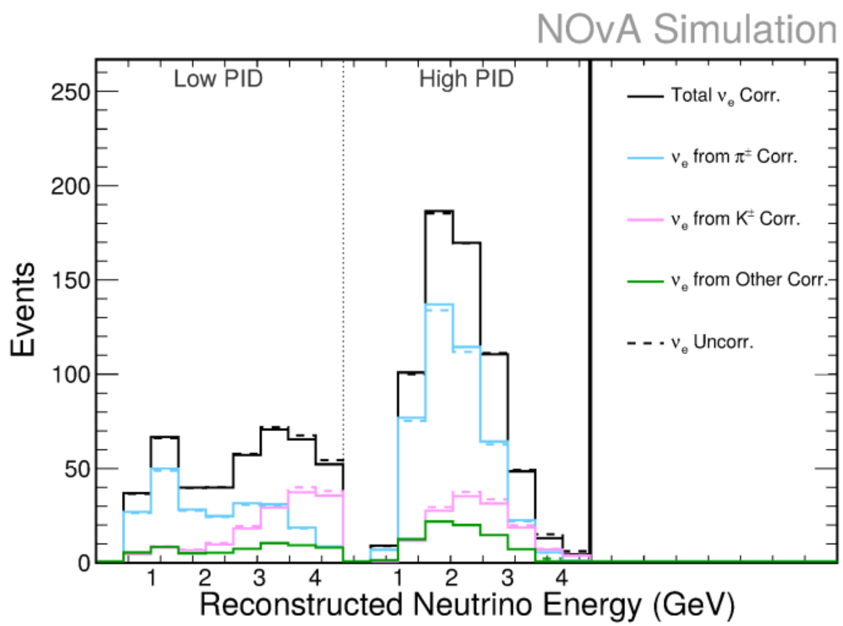
ν_e appearance: constraining beam ν_e bknd







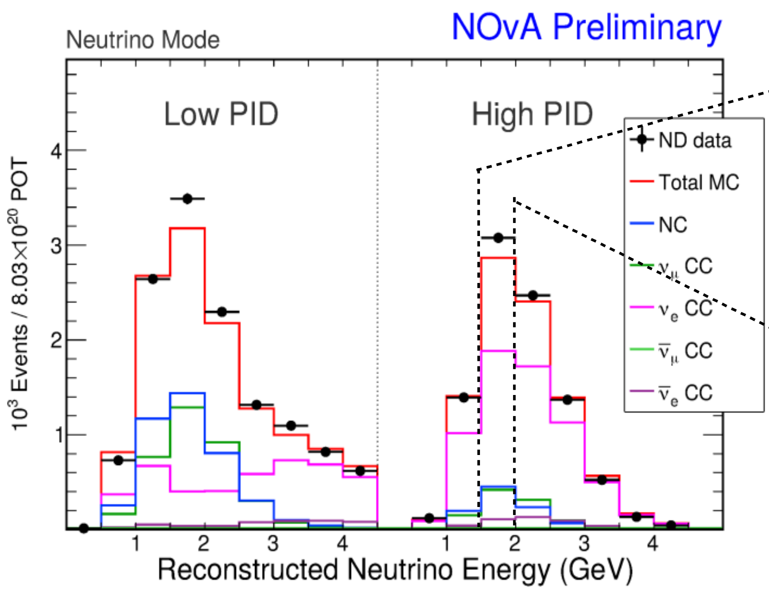
Assign discrepancies in ND ν_μ contained and uncontained samples to flux; **derive corrections according to parent mesons** (which also result in beam ν_e)

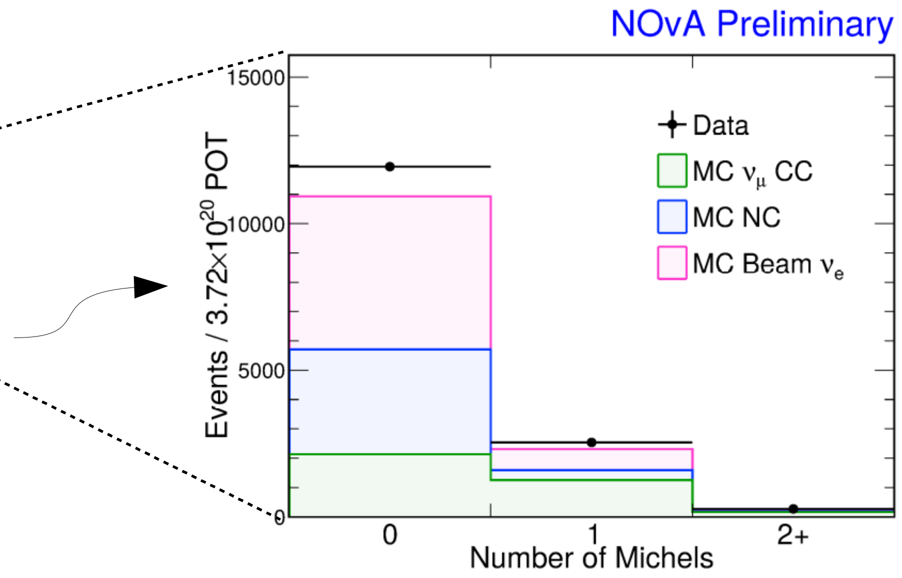


Pion-ancestor neutrinos are corrected in bins of parent (p_z, p_T). Average ~ +2%

Kaon-ancestor neutrinos get a single weight: -6.3%

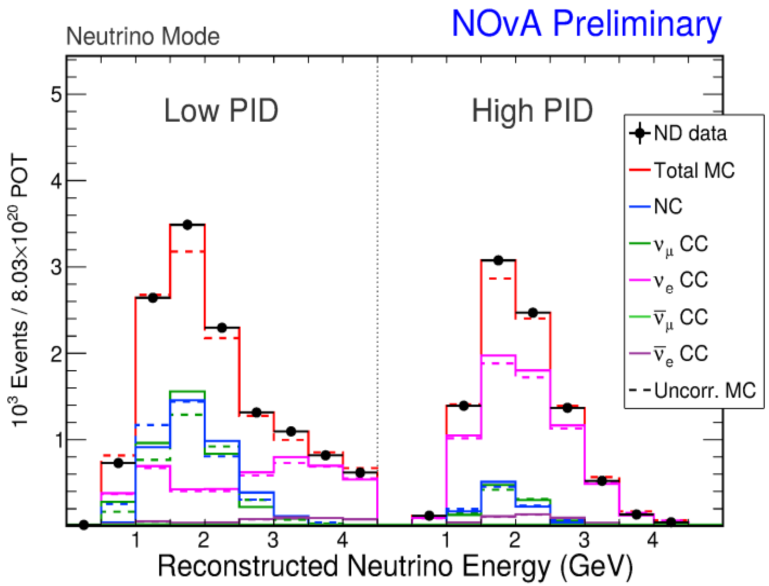
ν_e appearance: constraining ν_μ CC/NC ratio



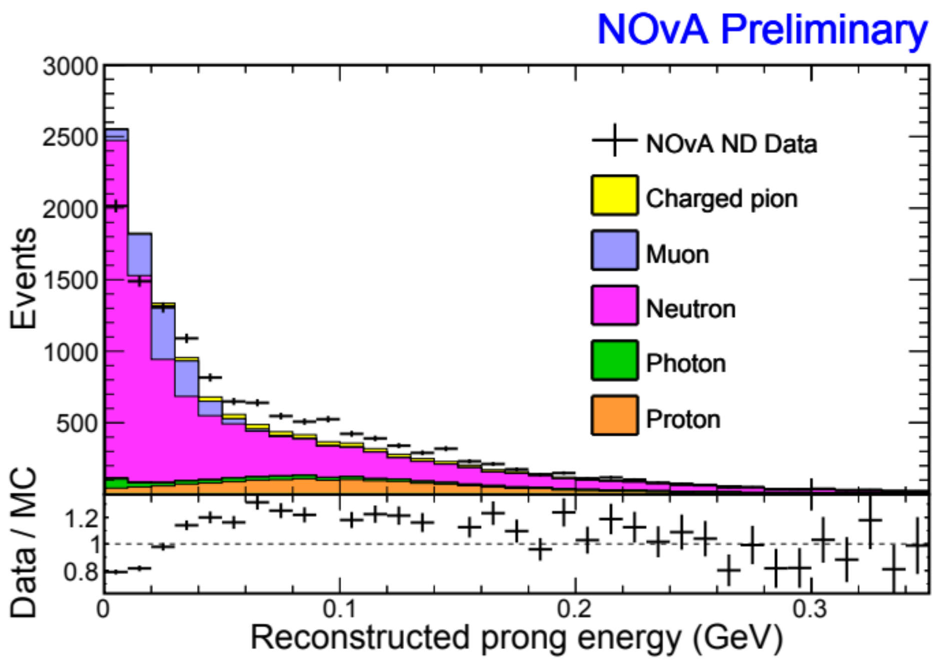


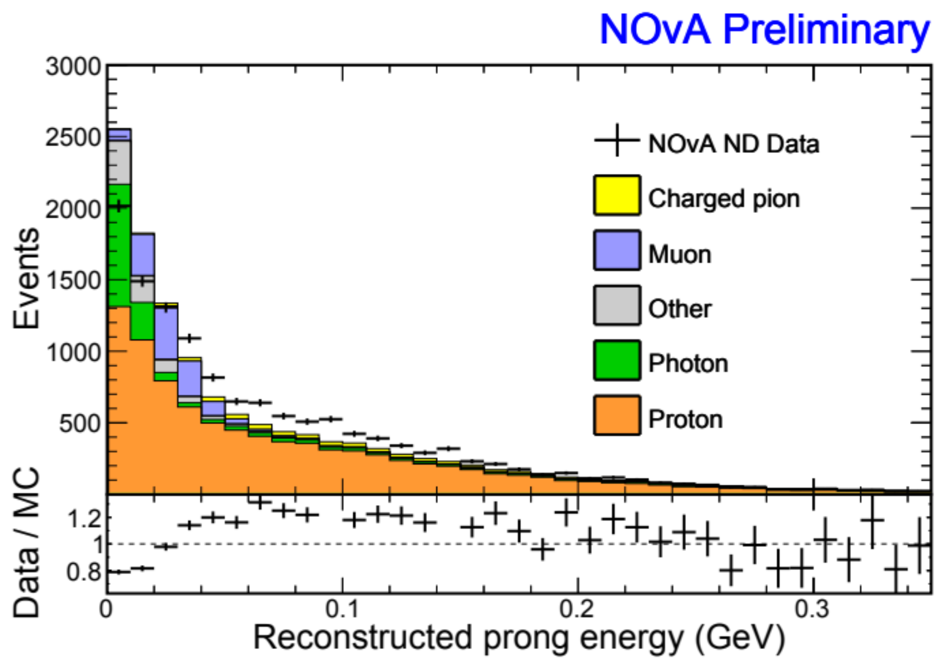
Examine distribution of Michel electrons in each bin of ND ν_e selected sample after beam ν_e constraint (prev slide)

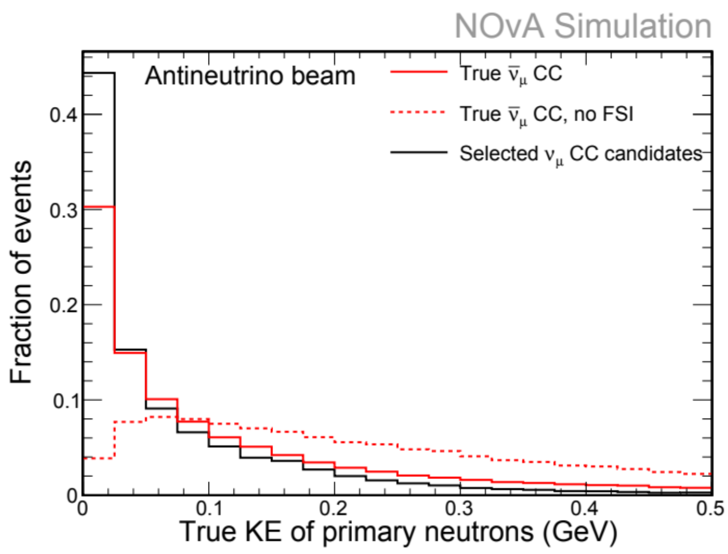
Fit these 18 distributions to determine ν_μ CC / NC corrections in each bin

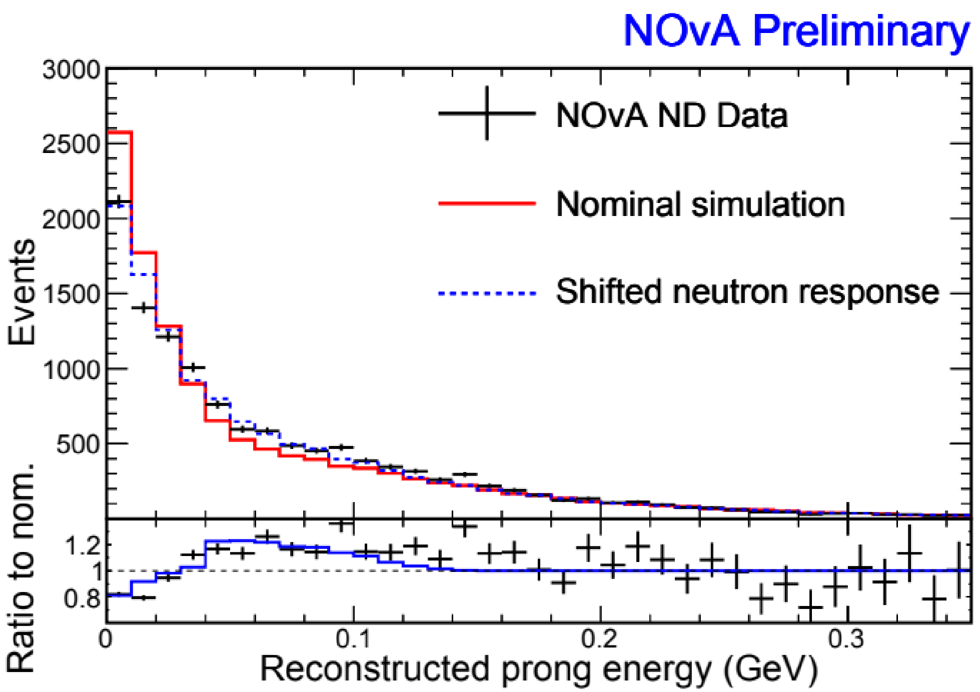


Neutron response



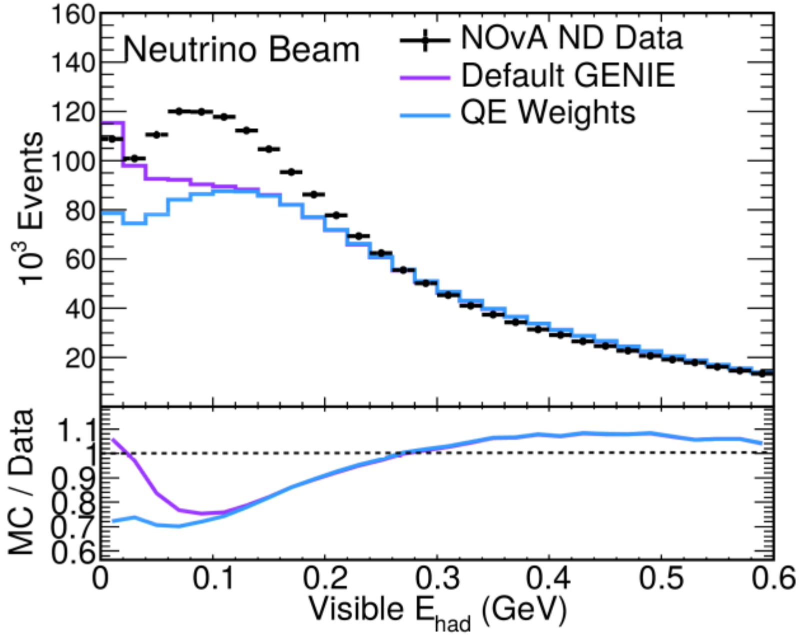






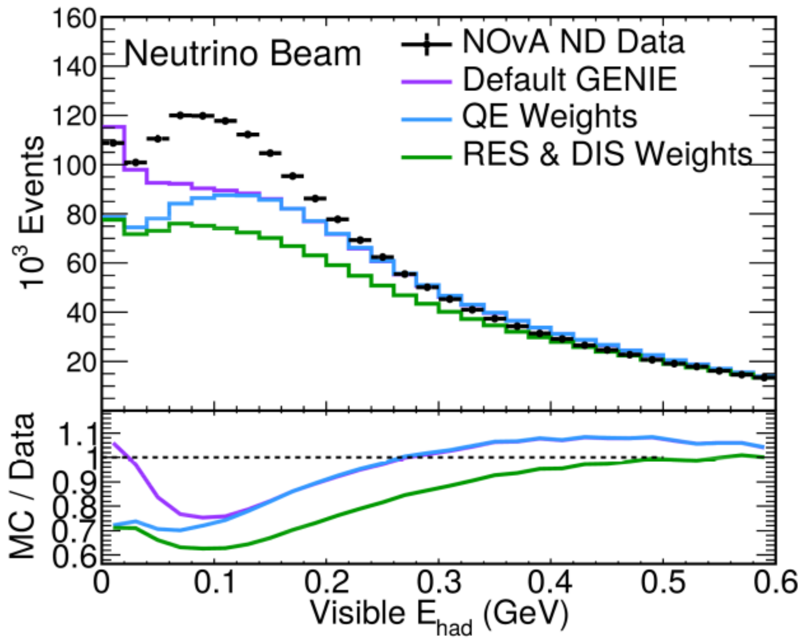
Cross section uncertainties: future needs

- More certainty about **1p1h initial state**
  - **RPA treatments differ in sophistication** - how much detail do we need?
  - **Uncertainties** (from València) **still large**, not completely canceled by extrapolation
  - **Binding/separation/removal energy** situation (A. Bodek, arXiv:1801.07975)...



Cross section uncertainties: future needs

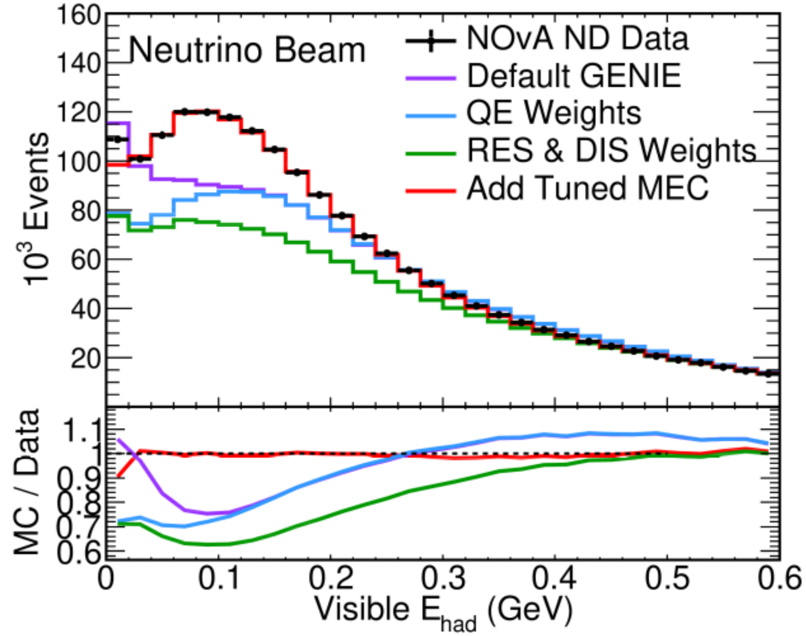
- **Nuclear models for *inelastic* processes** as well as QE
  - **Apparent low-Q^2 suppression relative to RFG suggests nuclear effects important**
    - Suggested by data (MINERvA+MINOS ND+MiniBooNE+NOvA ND)... no theory basis (yet?)
    - “On-off” treatment for syst one of our largest
  - Inelastic continuum at low E_ν
    - What does **“shallow” inelastic scattering on carbon at E_ν = 2 GeV** look like?
      - How does it interfere with RES? → GENIE uncertainties large
      - Free nucleon data helps only so much
    - Does **diffractive scattering from H** matter? How close are models?
- **ν_e/ν_μ differences for inelastic processes**
  - Current uncertainties are *ad hoc*



[NOvA has cross section measurements in progress which will help address some of these questions:
see L. Aliaga's and M. Judah's talks, next]

Cross section uncertainties: future needs

- More/better **models for multinucleon knockout** in GENIE
  - València model agrees poorly with MINERvA, NOvA ND data; **no alternatives in current versions** (but good things on the horizon?)
  - GENIE **assumes nucleon pair ejected isotropically**. Need ("semi-inclusive") models for what should *really* happen
  - Empirical tuning procedure doesn't prescribe **correlations between ν and $\bar{\nu}$** – so left uncorrelated...



Cross section uncertainties: future needs

- **Much more $\bar{\nu}$ scattering data**
  - Every issue mentioned above applies also for antineutrinos, only there are **fewer data constraints**
  - Abundance of fast neutrons an interesting challenge for calorimetry: **final-state particle measurements** especially helpful