Impact of cross section uncertainties on NOvA oscillation analyses

on behalf of the NOvA collaboration

Jeremy Wolcott
Tufts University

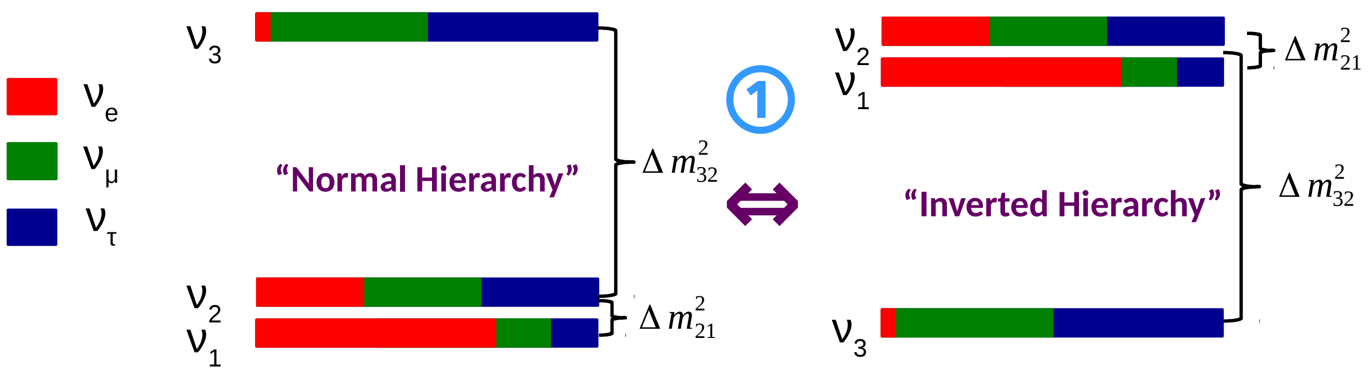
June 25, 2017
NuInt 2017 (Toronto, Canada)

The NOvA experiment

A broad neutrino physics program

- <u>Engaging major questions in oscillation physics:</u>

  ① How are the mass eigenstates ordered?



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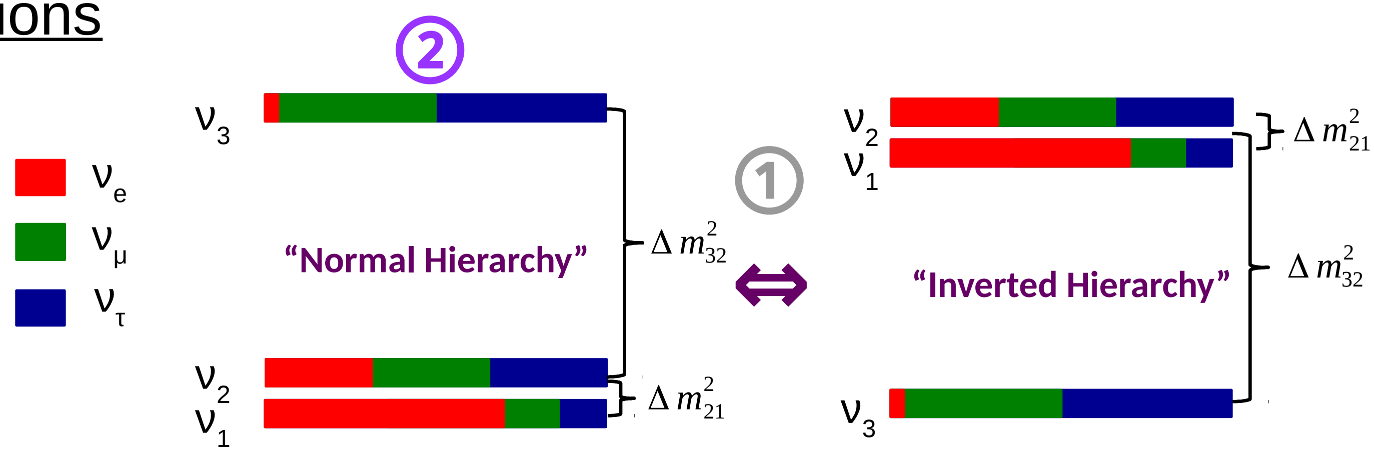

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12}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

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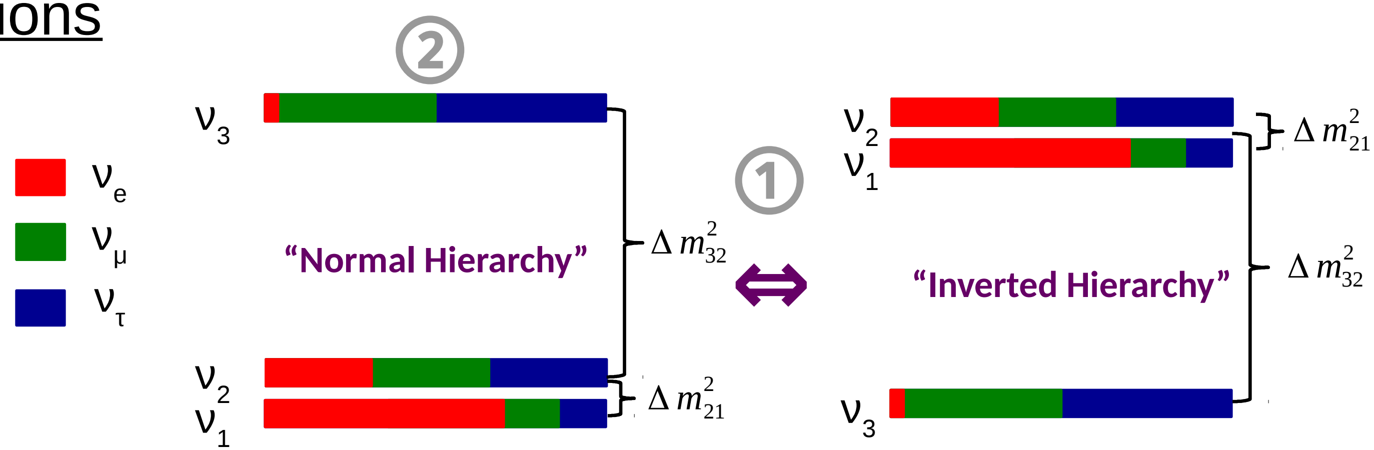

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③ Is there CP violation in leptons?

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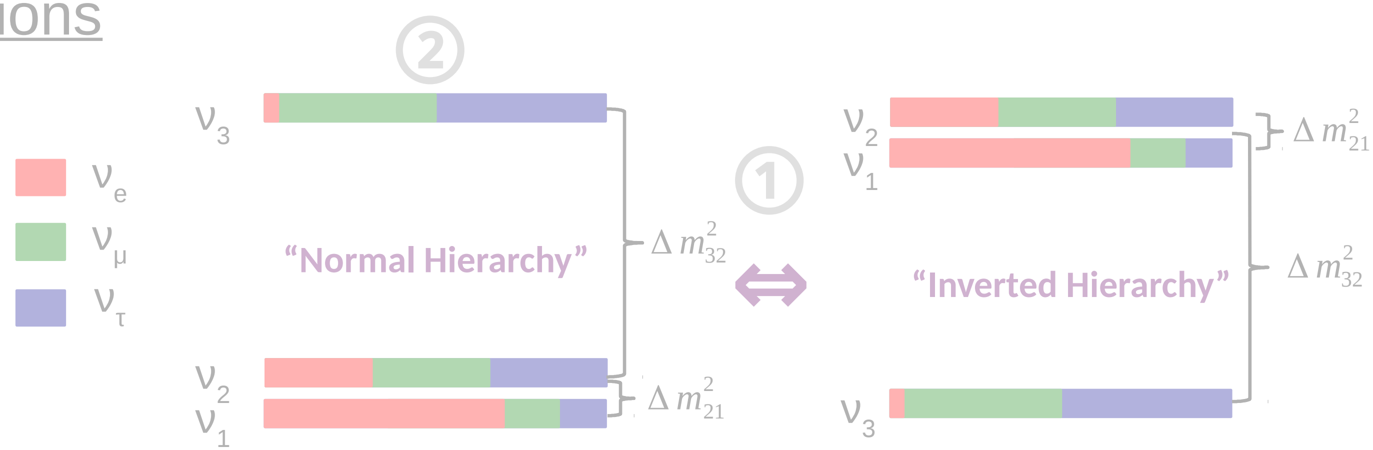

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- Searching beyond the Standard Model:

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

The NOvA experiment

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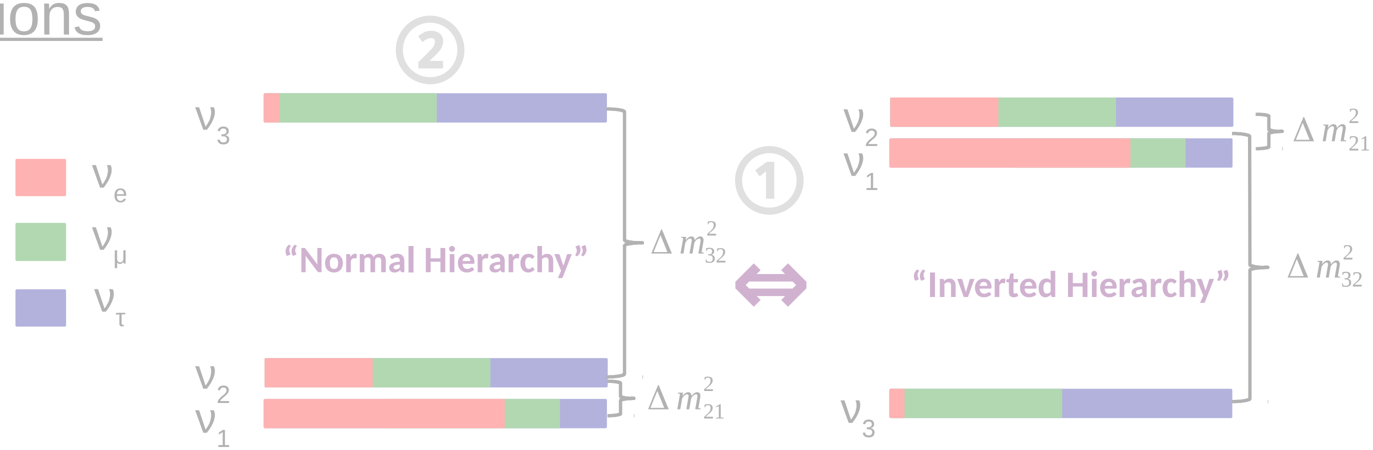

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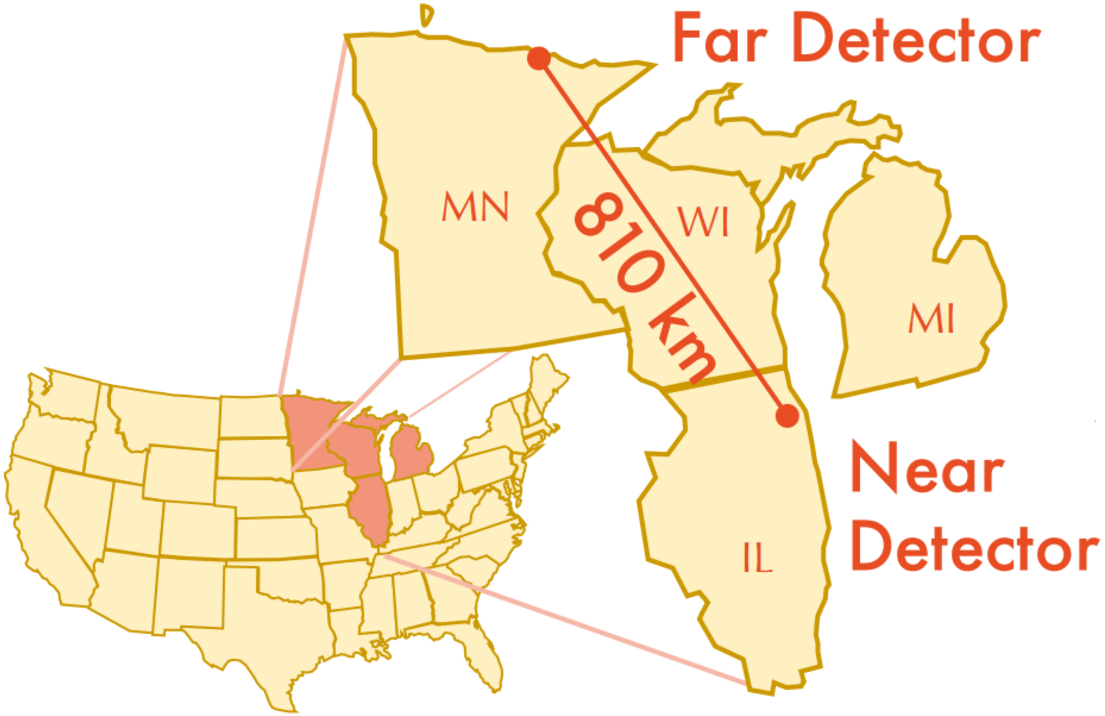
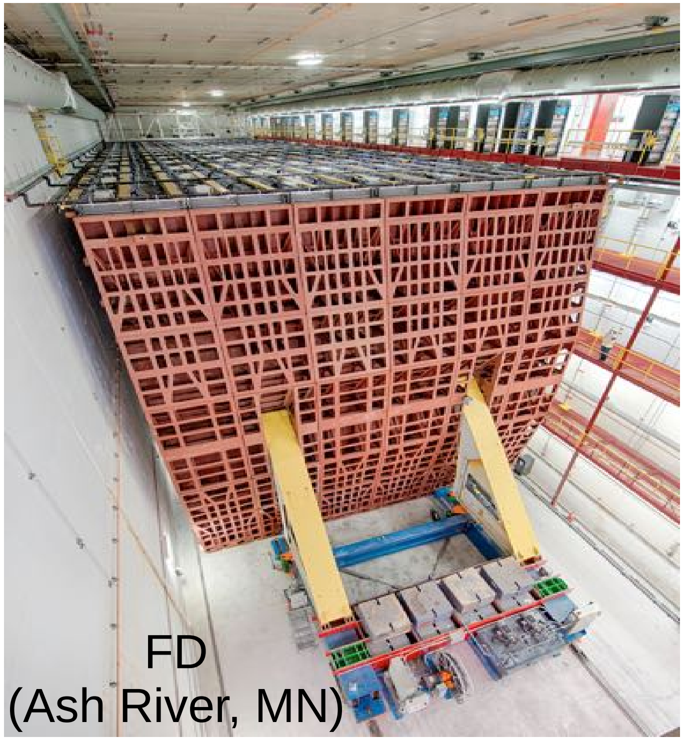
  ...

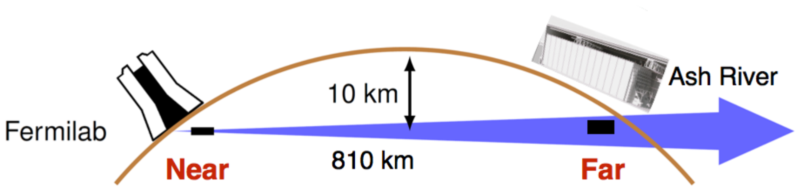
- Cross section measurements:

  J. Paley's talk, Mon. June 26
  H. Duyang's talk, Tues. June 27

The NOvA experiment

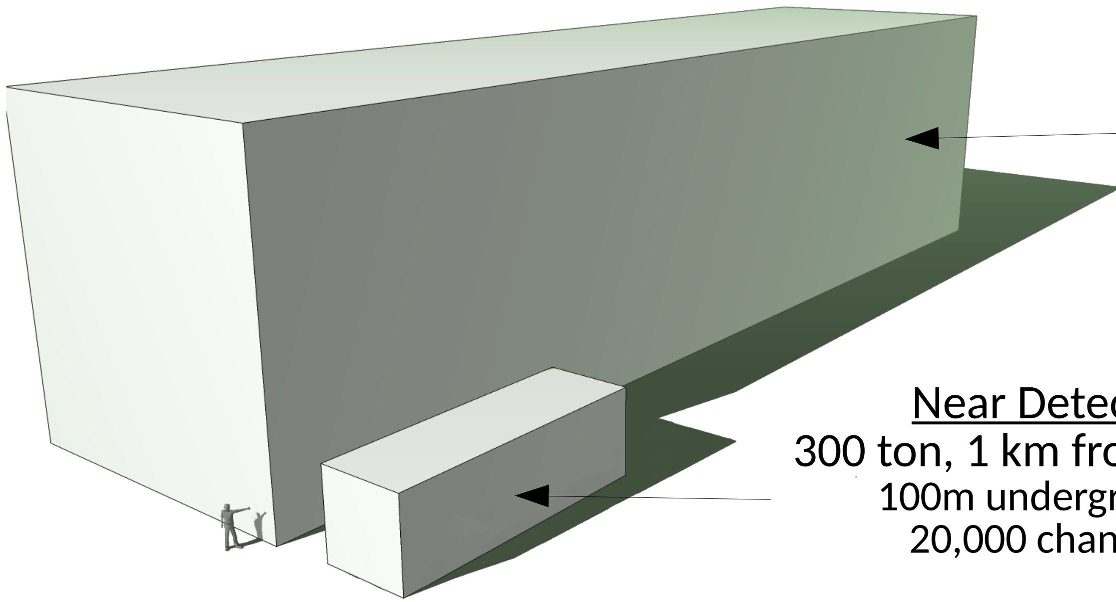






NuMI neutrino beam discussed in detail by L. Aliaga on Mon. June 26

The NOvA experiment



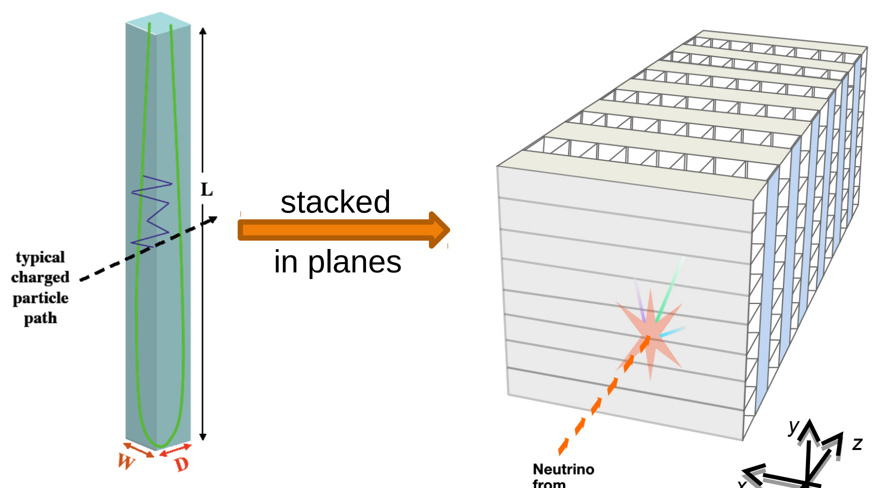
<u>Far Detector</u>
14 kton, 810 km from source
On the surface
(3m concrete+barite overburden)
344,000 channels

<u>Near Detector</u>
300 ton, 1 km from source
100m underground,
20,000 channels

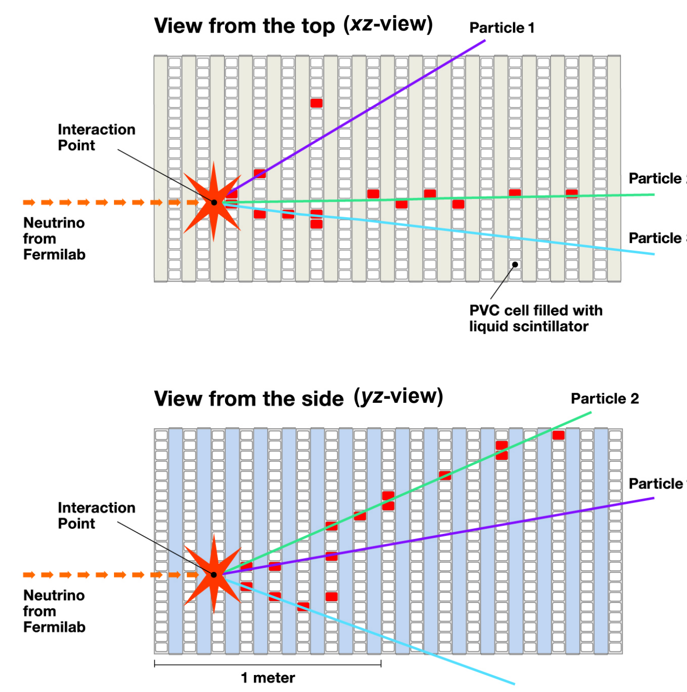
Functionally identical detectors

Sampling calorimeter detectors
(Radiation length ~40 cm: 6 samples per radiation length. Good E_{lep}, E_{had} resolution)

1 Channel

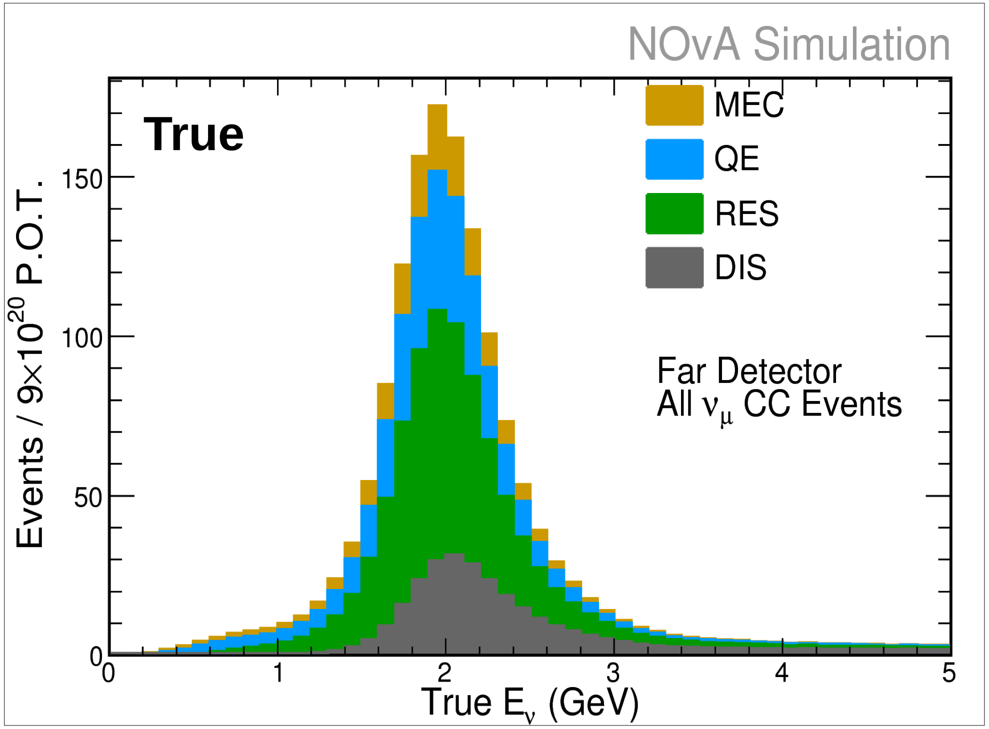


(4cm × 6cm)



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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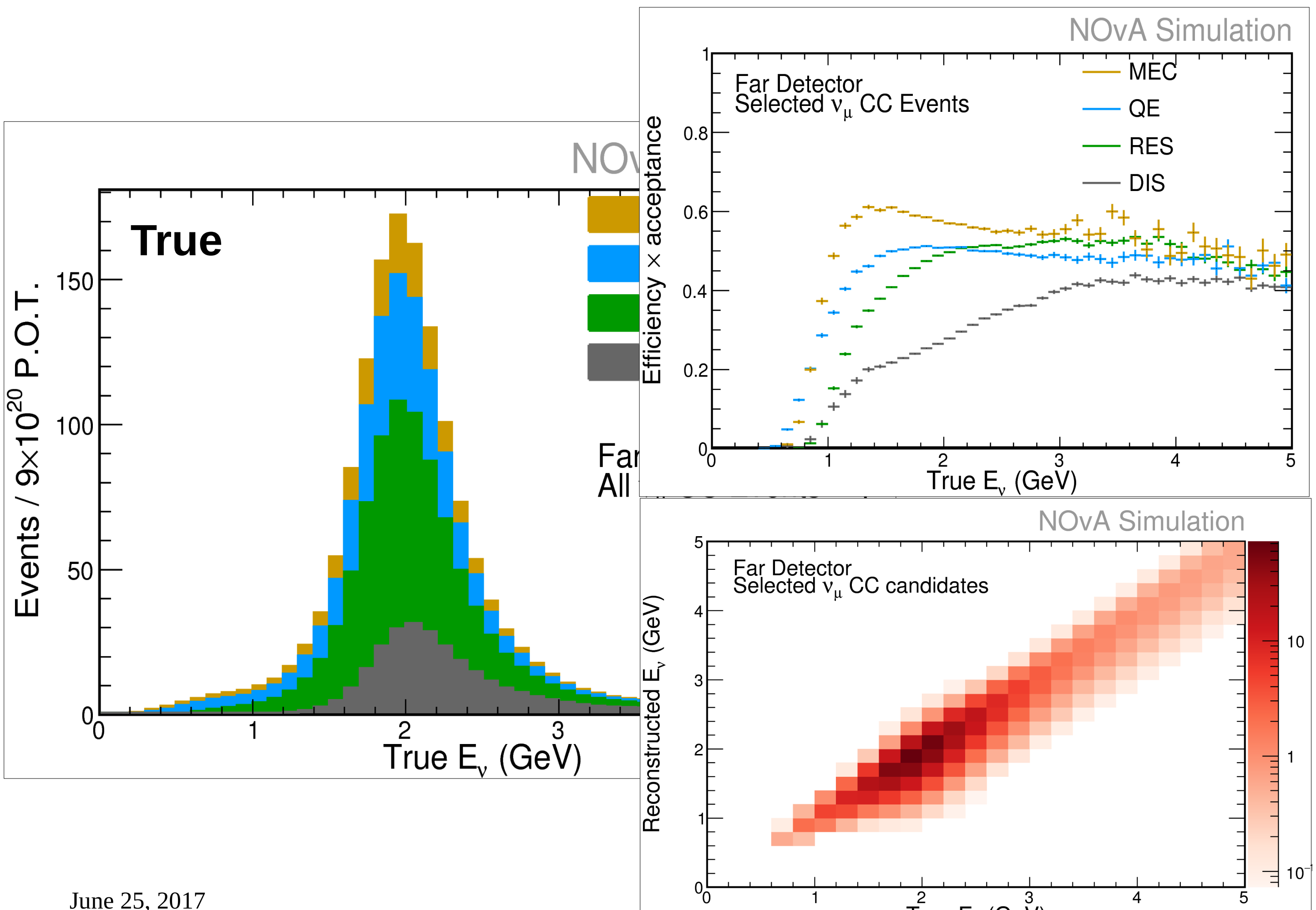

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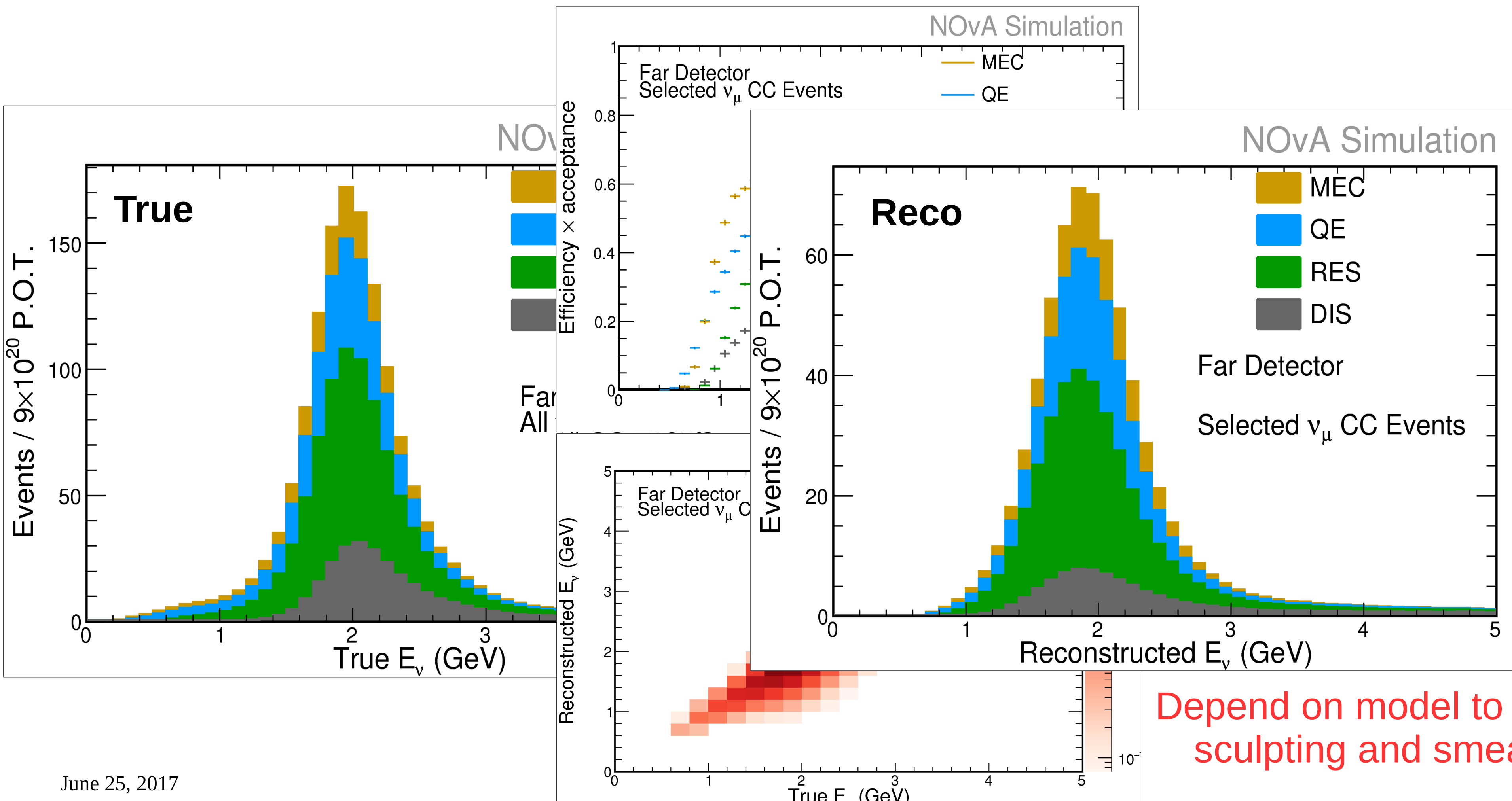
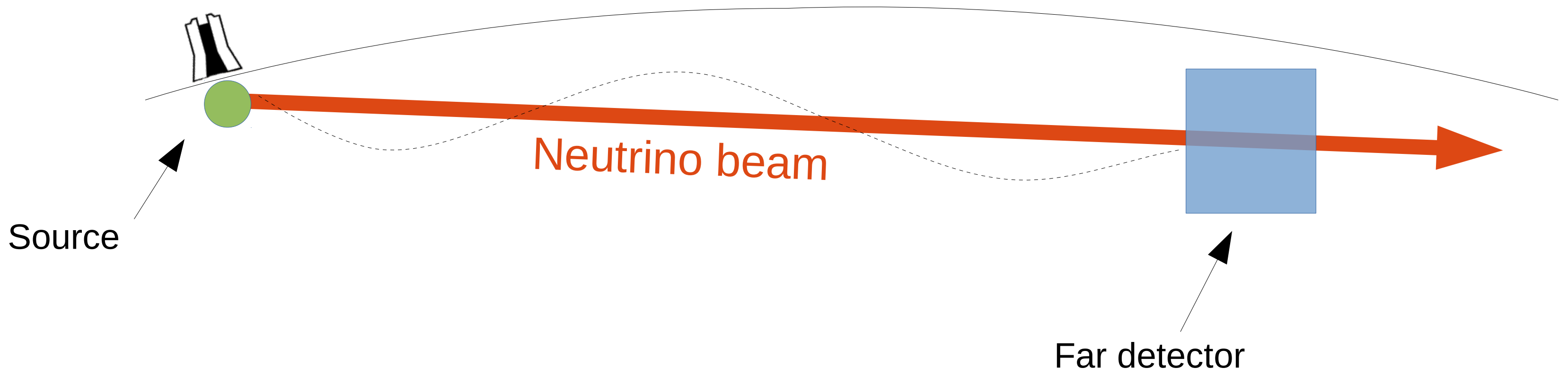


Depend on model to predict sculpting and smearing

Near detectors

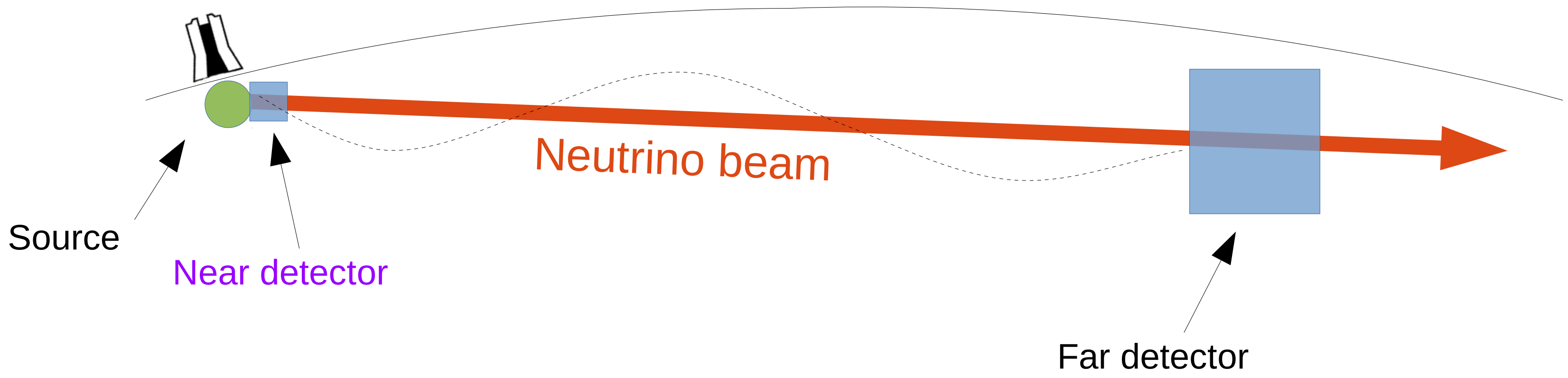


The event rate measured at the far detector is a complicated function of many things, not just oscillation probability:

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

Both low statistics at the FD (typically 10s-100s of events) and systematics on the other parameters can blur the oscillation probability effect.

Near detectors



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A Near Detector helps in two ways:

- Much better stats
- No oscillations (fewer DoFs)

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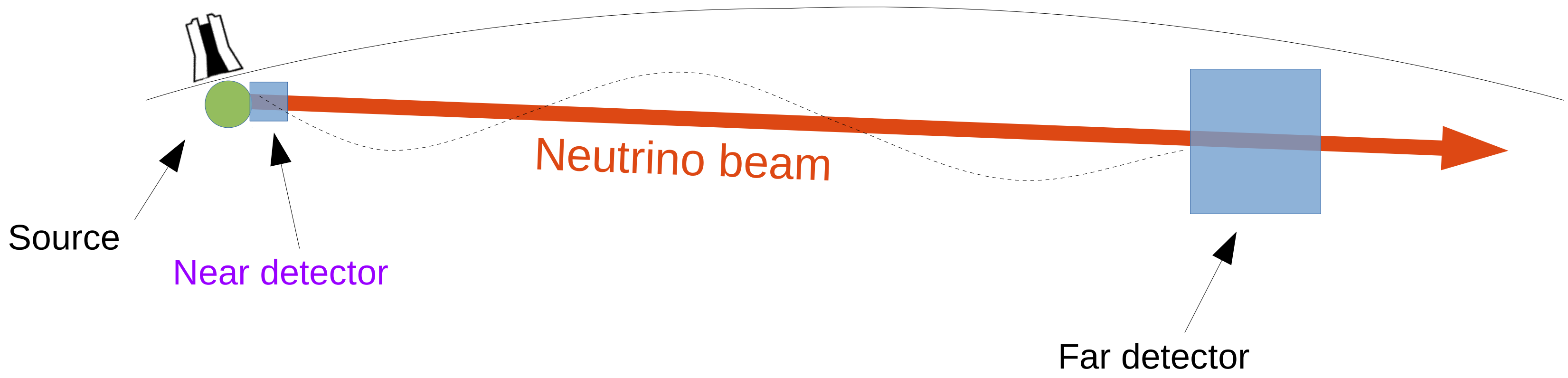

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A Near Detector helps in two ways:

- Much better stats
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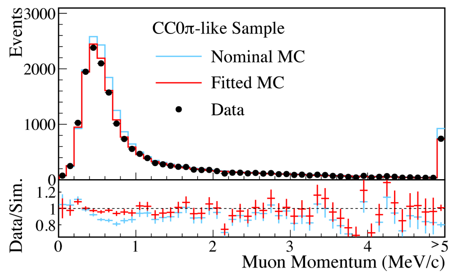
Exploit correlations as much as possible

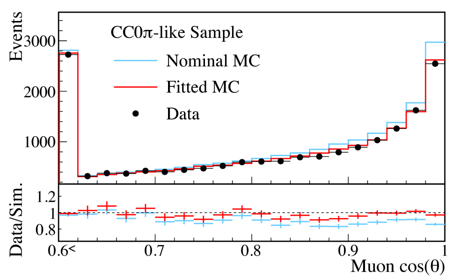
$$N^{ND}(E_\nu^{rec}) = \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(\ldots)$$

Using the ND

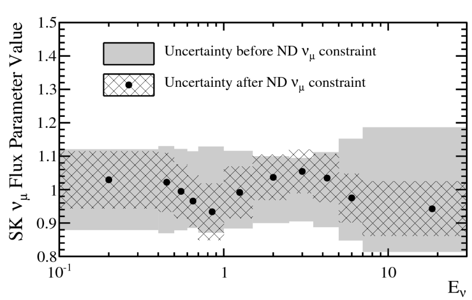
Strategy #1
Fit ND (T2K)

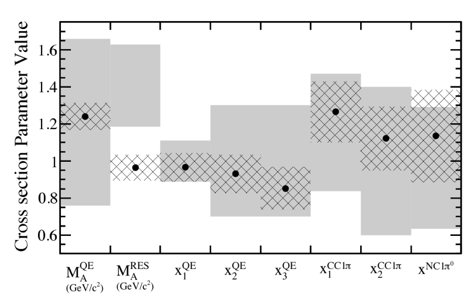
PRD 91, 072010





Float parameters corresponding to uncertainties in fits to ND distributions

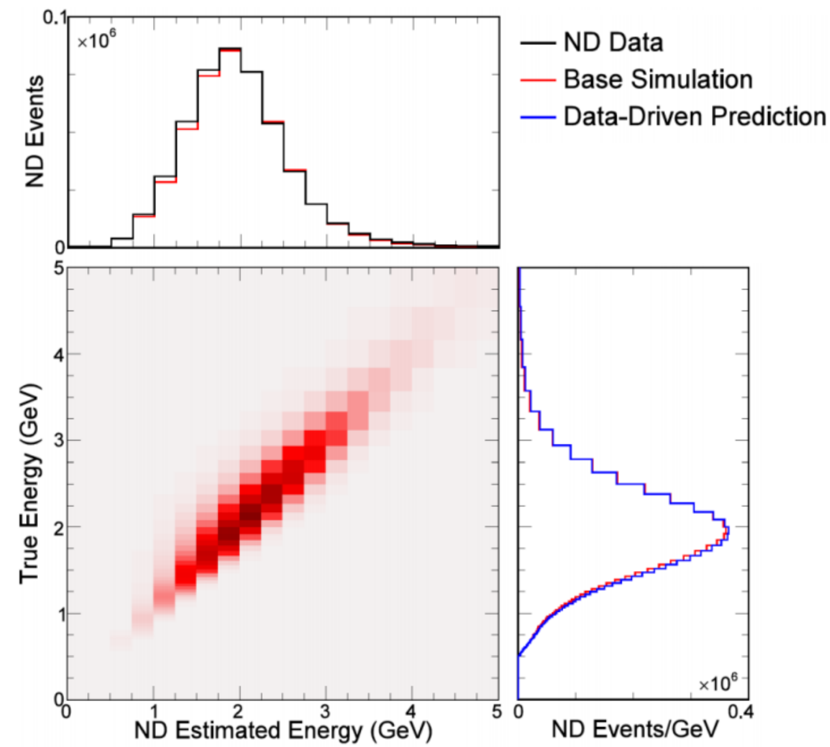




Use resulting fitted central values and systematic covariances as input to FD (oscillation) fit

[see S. Dennis's talk, T2K, next!]

Strategy #2
Spectrum correction (MINOS, NOvA)



Reweight true energy distribution to obtain data-MC agreement at ND and extrapolate to FD using simulated F/N ratio; repeat for each systematic to determine constrained effect of systs at FD

Using the ND

Strategy #1
Fit ND (T2K)

Strategy #2
Spectrum correction
(MINOS, NOvA)

Strengths

Strategy #1:

- ✔ Completely general (works for any expt design)
- ✔ Builds on physical understanding of underlying processes (models)

Strategy #2:

- ✔ Efficiently *cancel* strongly correlated uncertainties between ND & FD
- ✔ Can account for discrepancies without fully formed model

Weaknesses

Strategy #1:

- … Relies on exhaustiveness of models and associated parameters (“best fit” not guaranteed to fit data)

Strategy #2:

- … Very little constraint power if uncertainties affect detectors in different ways

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)

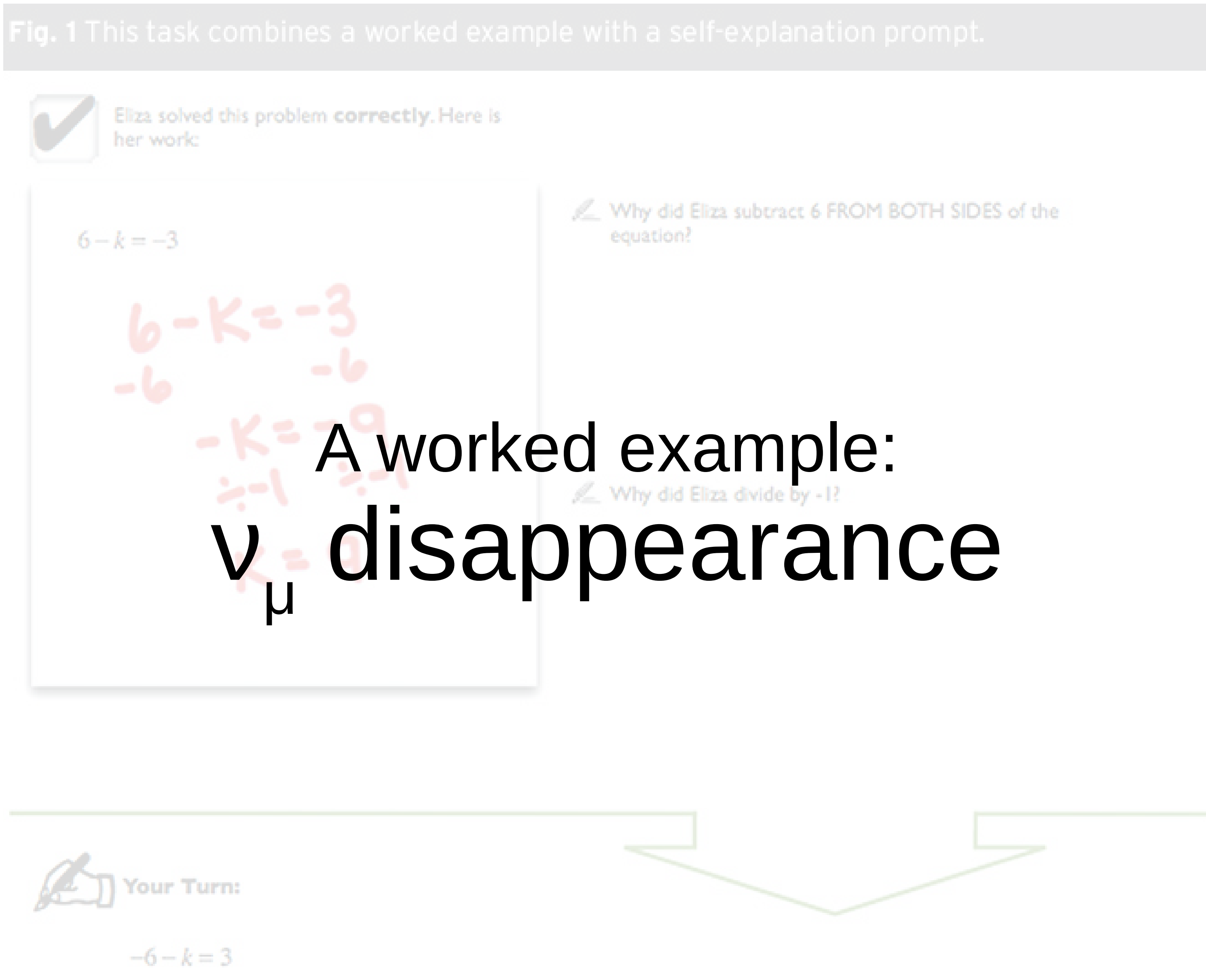
… with special studies for nonreweightable knobs...

Hadronization uncertainties

…and a few custom knobs where GENIE doesn't offer any:

MEC model for **2p2h**

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



A worked example:

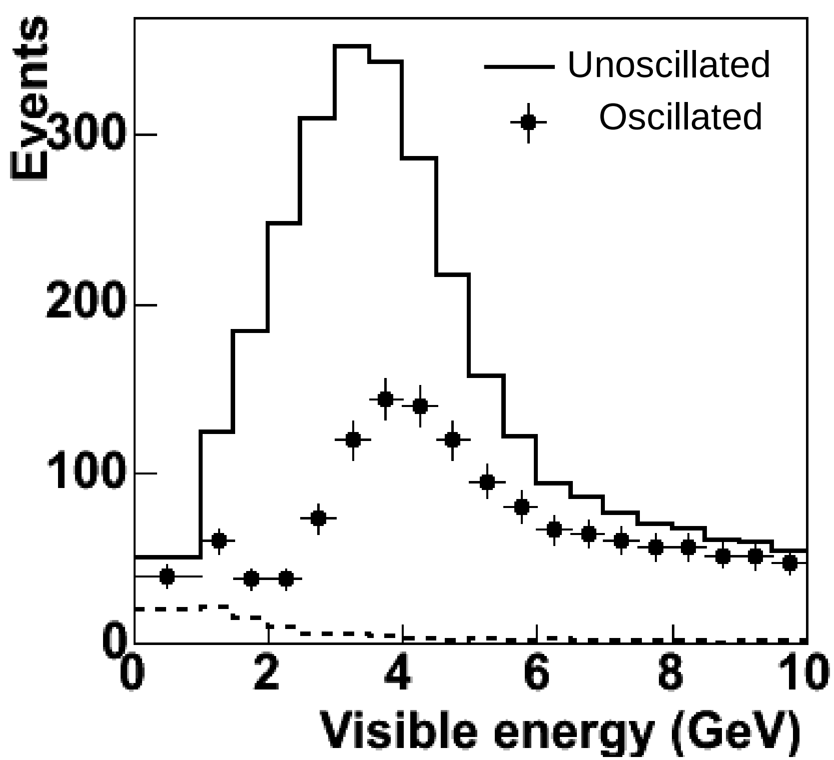
ν_μ disappearance

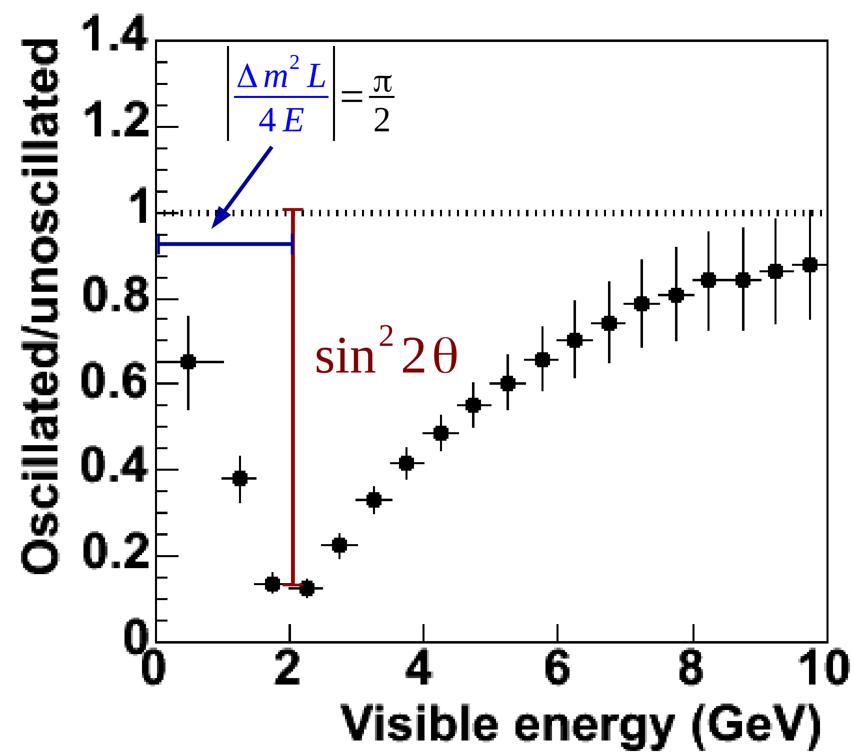
ν_μ disappearance

ν_μ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

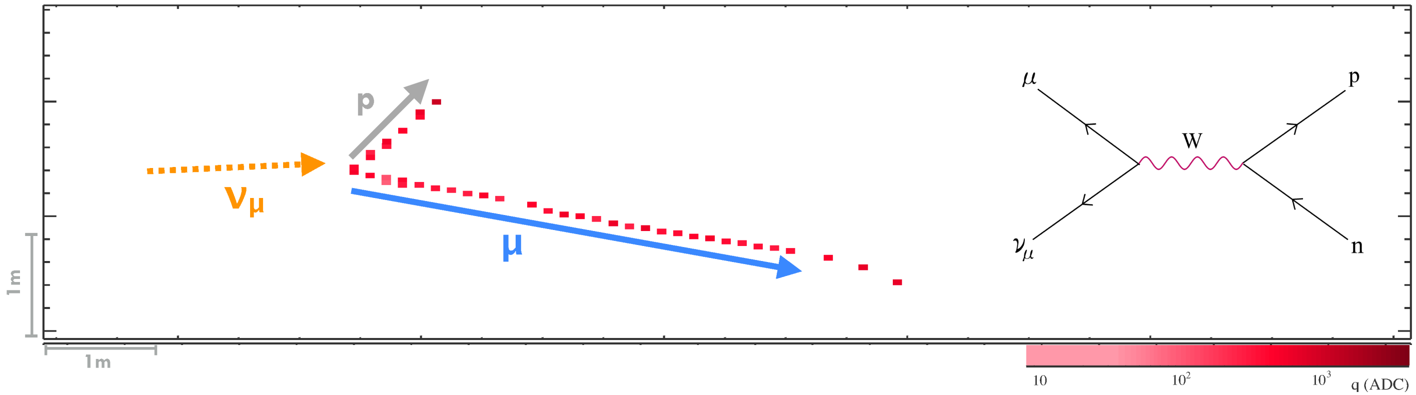
... to leading order

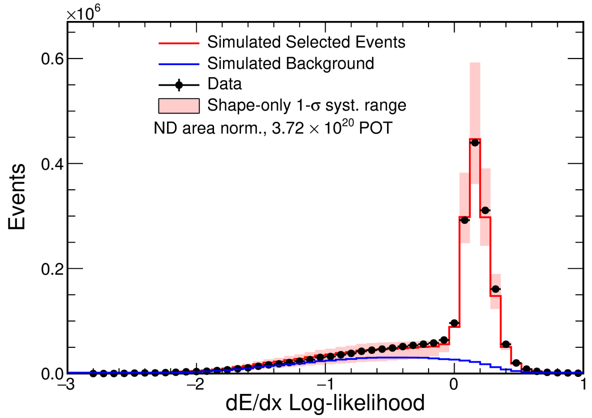




Goal: measure the location and strength of the "oscillation dip" relative to no-oscillations prediction

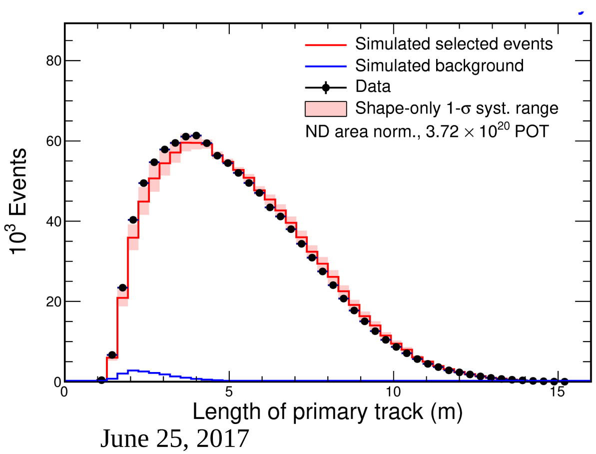
ν_μ disappearance: selection

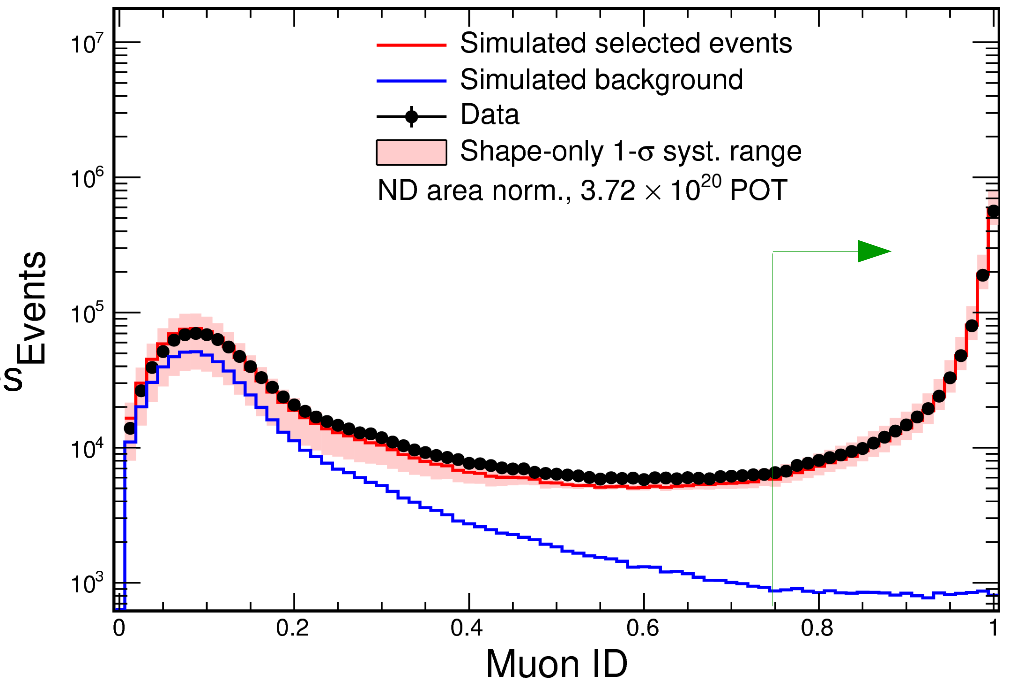




kNN-based ν_μ CC classifier uses 4 inputs:

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

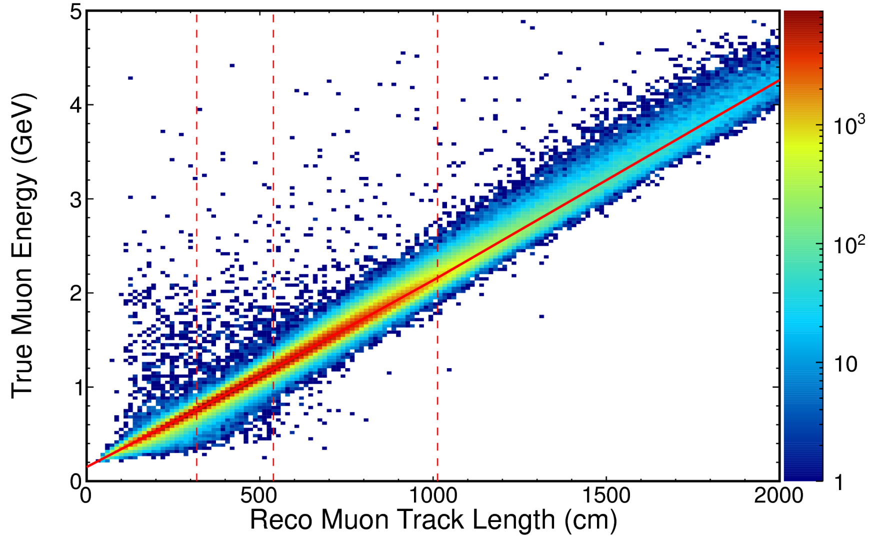




ν_μ disappearance: energy reconstruction

E_{lep} | E_{had}

E_ν =



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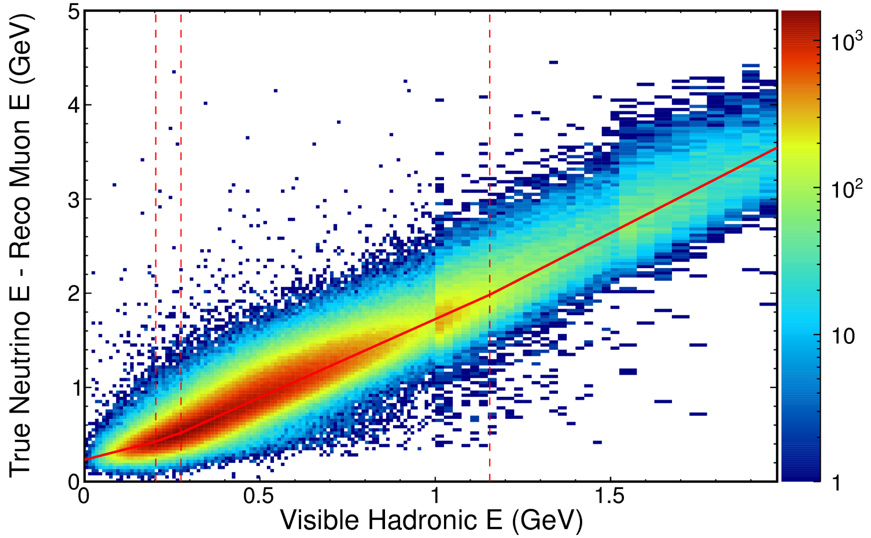
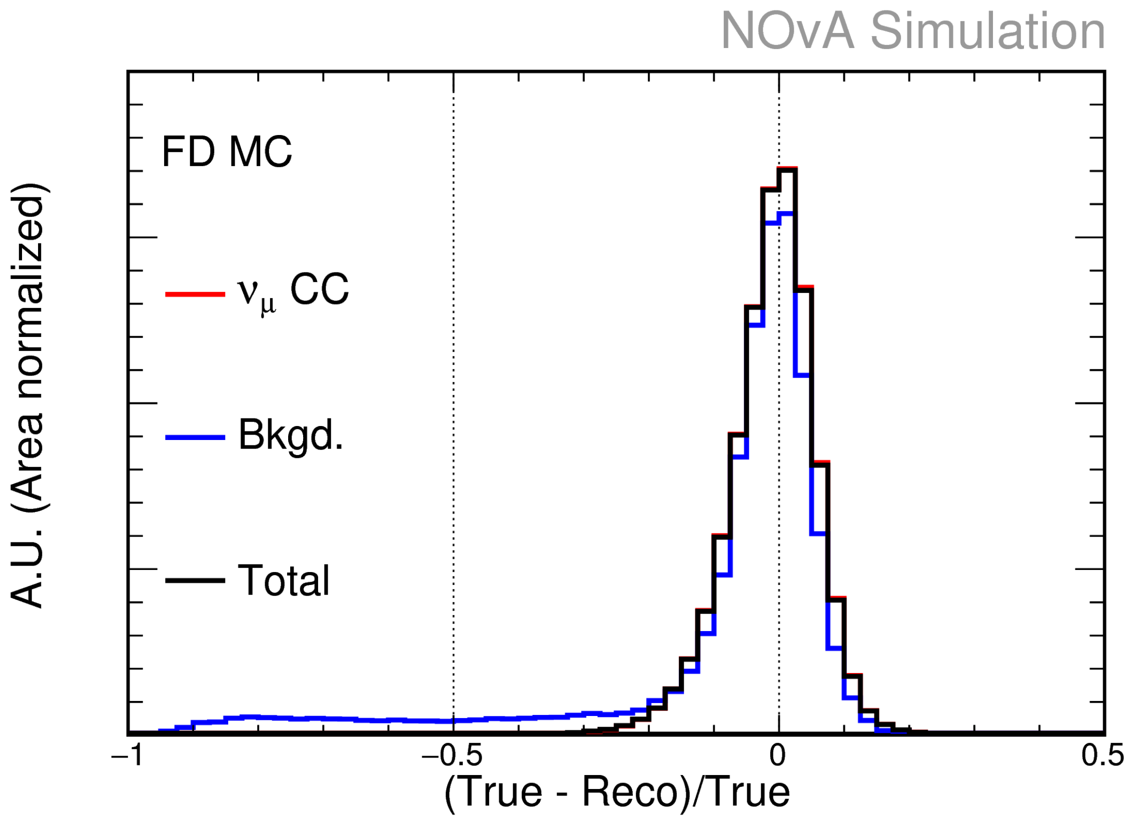


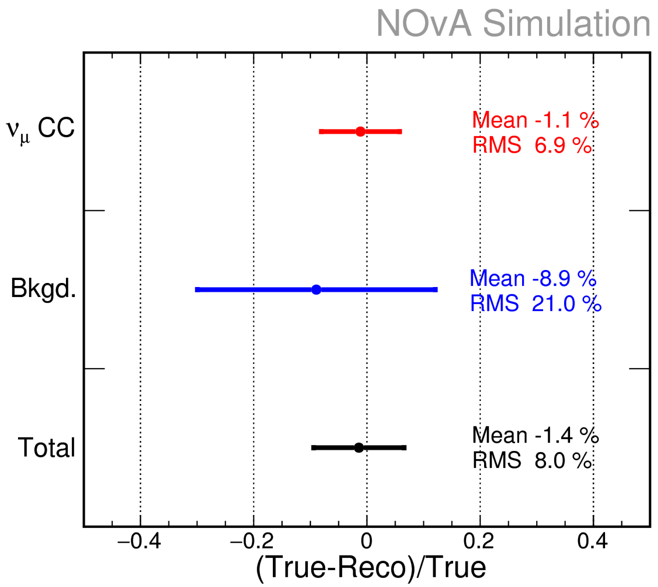
(~3% resolution) | (~15% resolution)

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

Calorimetric (not kinematic) energy reconstruction

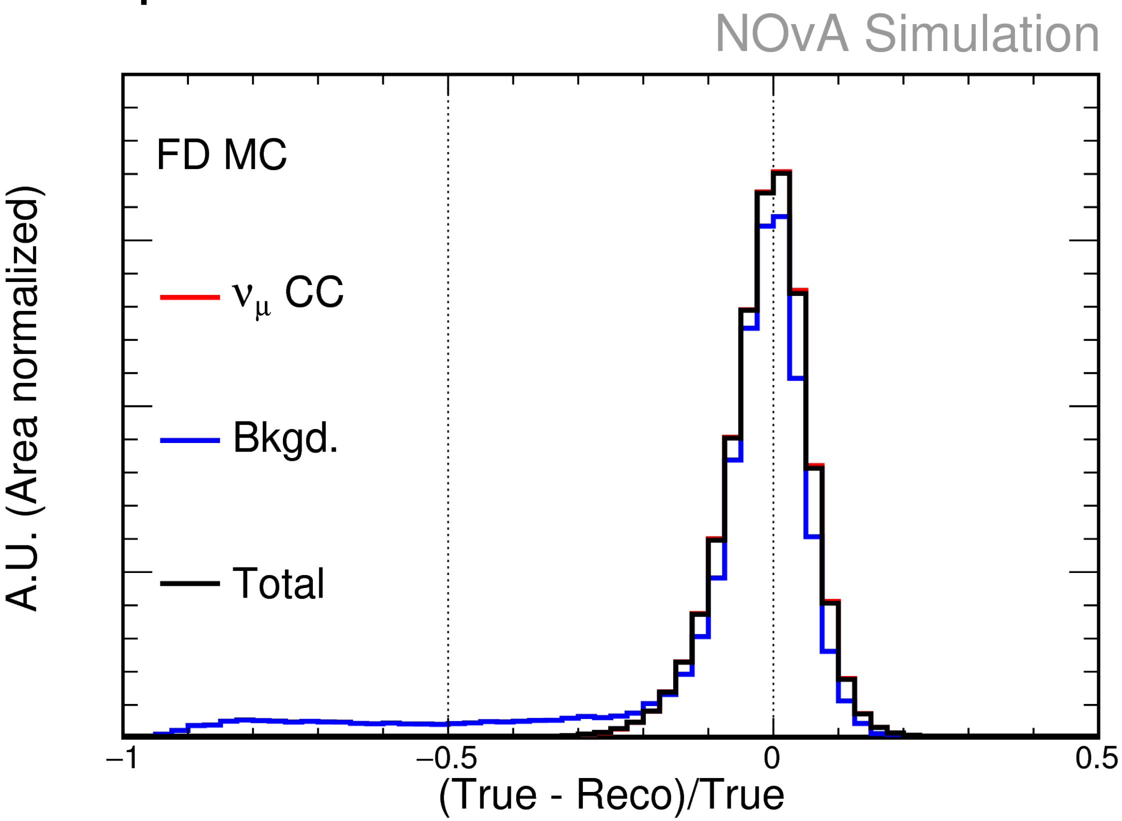
ν_μ disappearance: energy reconstruction

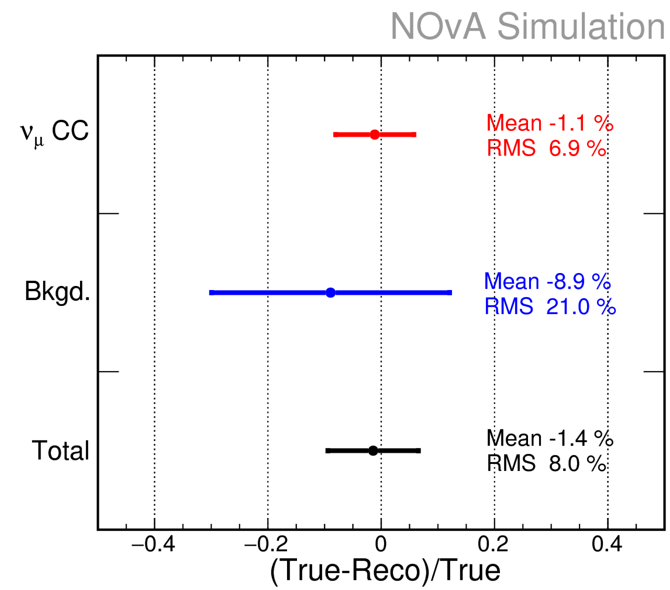




Nominal resolution on E_ν ~ 7%.

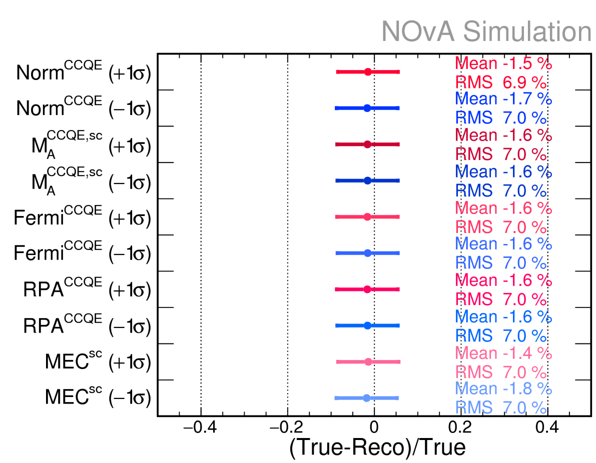
ν_μ disappearance: energy reconstruction

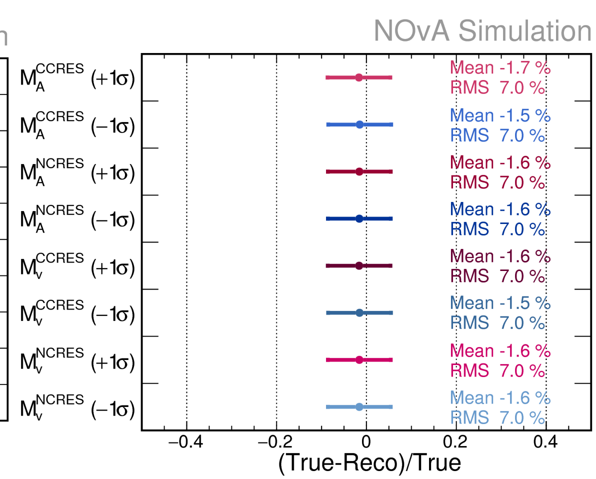




Nominal resolution on E_ν ~ 7%.

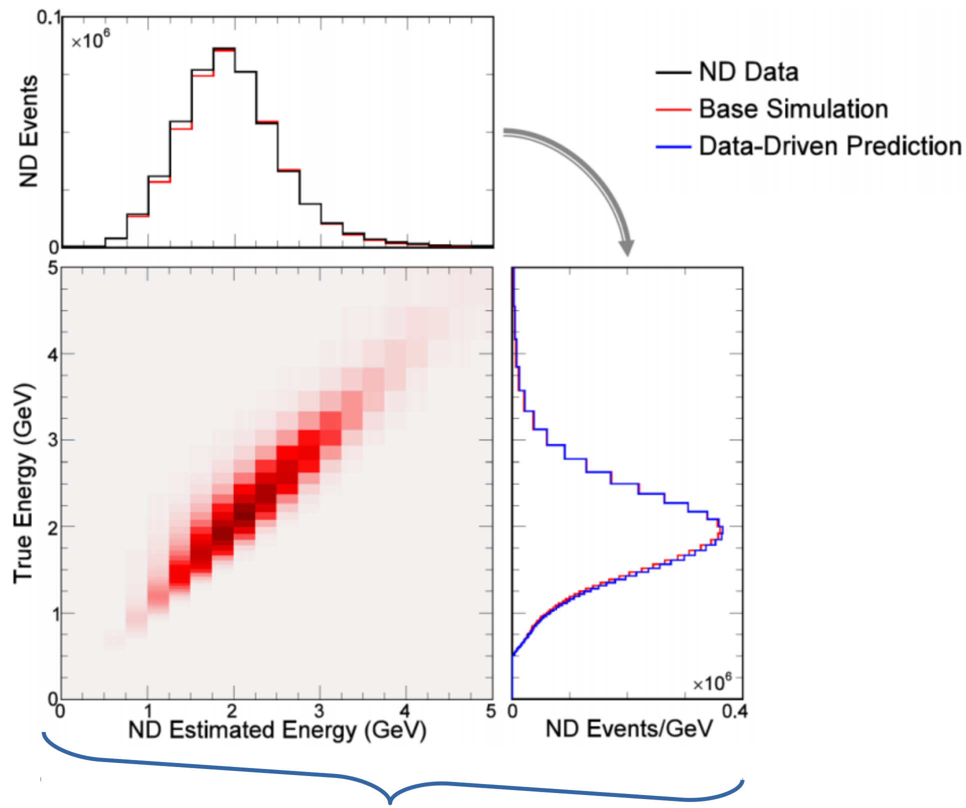
Despite sculpting effect, calorimeter-style detectors ensure **cross section systematics** (which mostly change E_{lep}/E_{had} balance) **don't significantly degrade energy resolution**





ν_μ disappearance: "extrapolation"

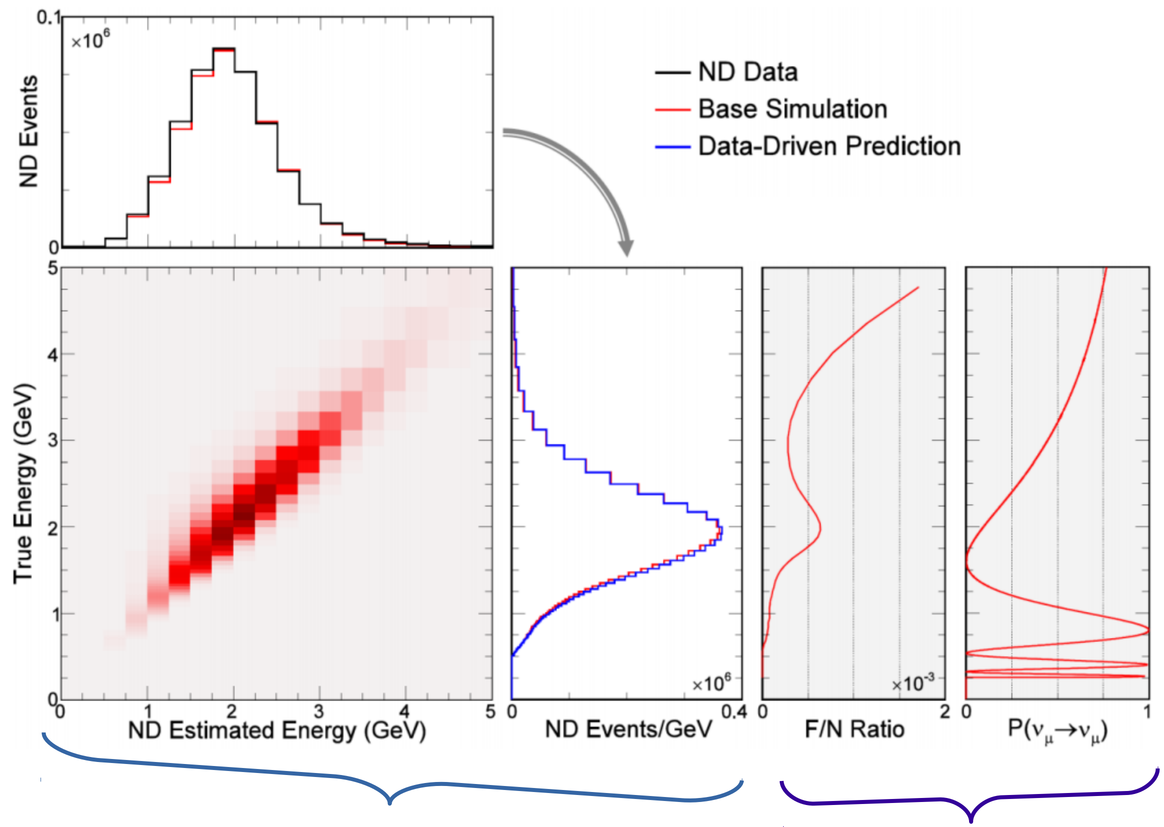
To produce a data-driven prediction at FD, based on ND:



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

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...

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

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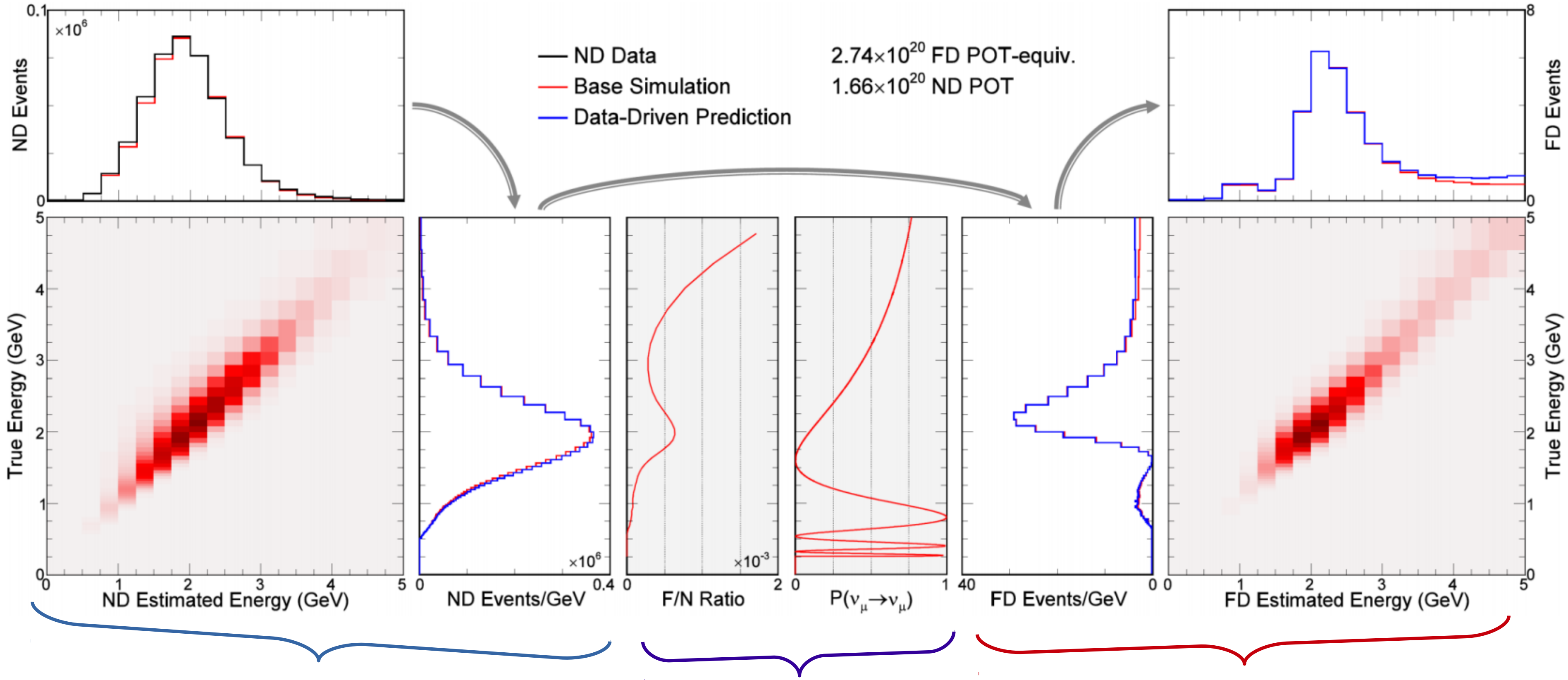

True energy distribution is corrected so that reconstructed data & MC agree at the ND...

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

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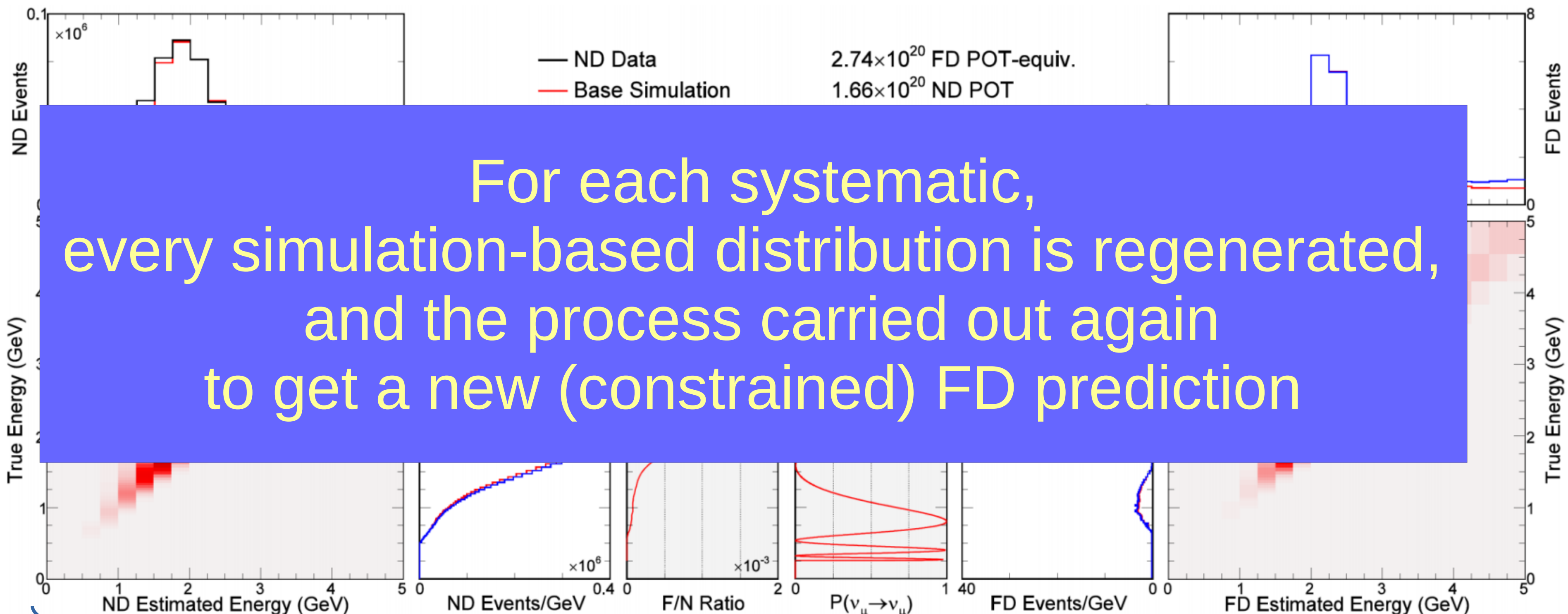

For each systematic,
every simulation-based distribution is regenerated,
and the process carried out again
to get a new (constrained) FD prediction

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

Illustrating XS systematics: MEC

Examine this procedure through the lens of reaction that's historically gotten a lot of press at NuInt:

2p2h

via

Meson Exchange Currents

(CV: GENIE 'Empirical MEC' w/ ND tuning)

Published analyses use

50% normalization uncertainty

(more sophisticated treatment in future)

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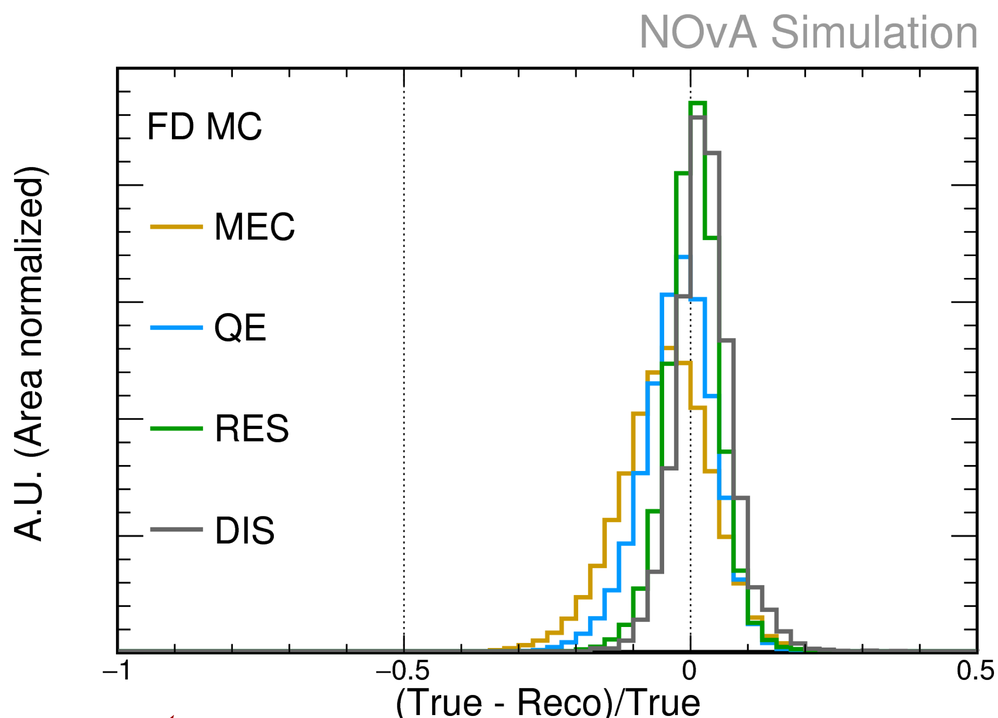

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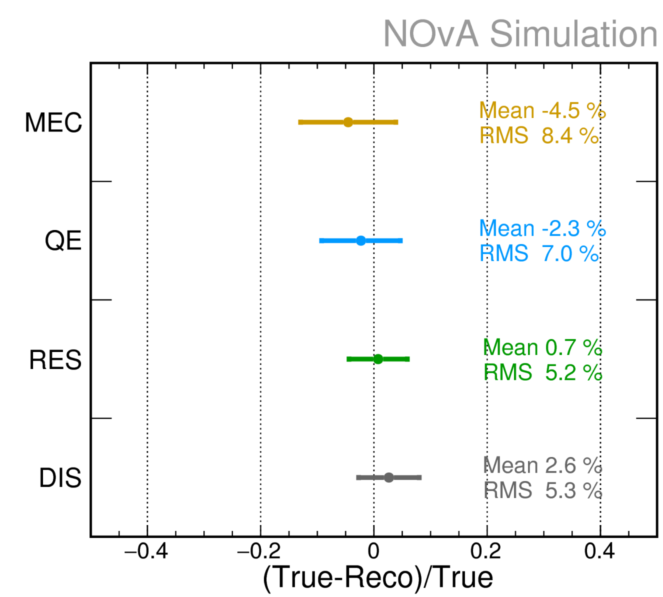
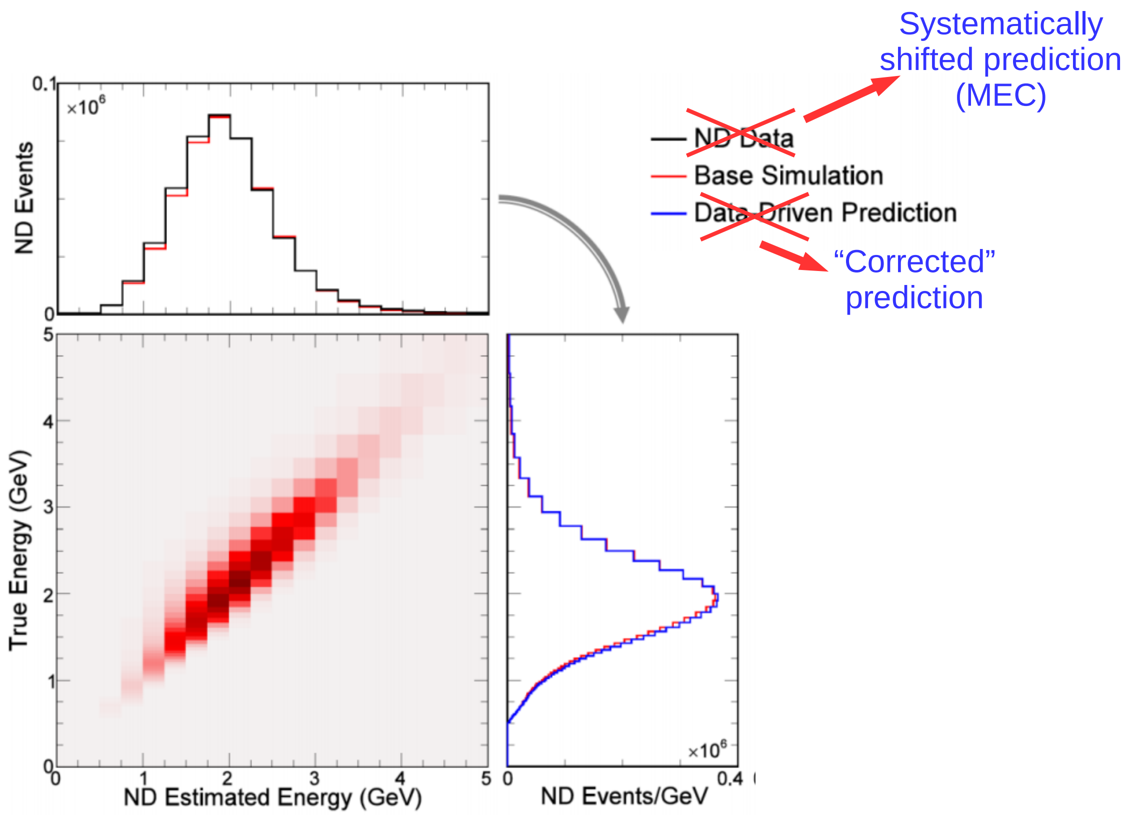
Energy resolution is a function of reaction type.



If "extrapolation" really works, even <u>changing the composition</u> (adding/subtracting MEC) <u>should have minimal effect at FD.</u>

Testing extrapolation

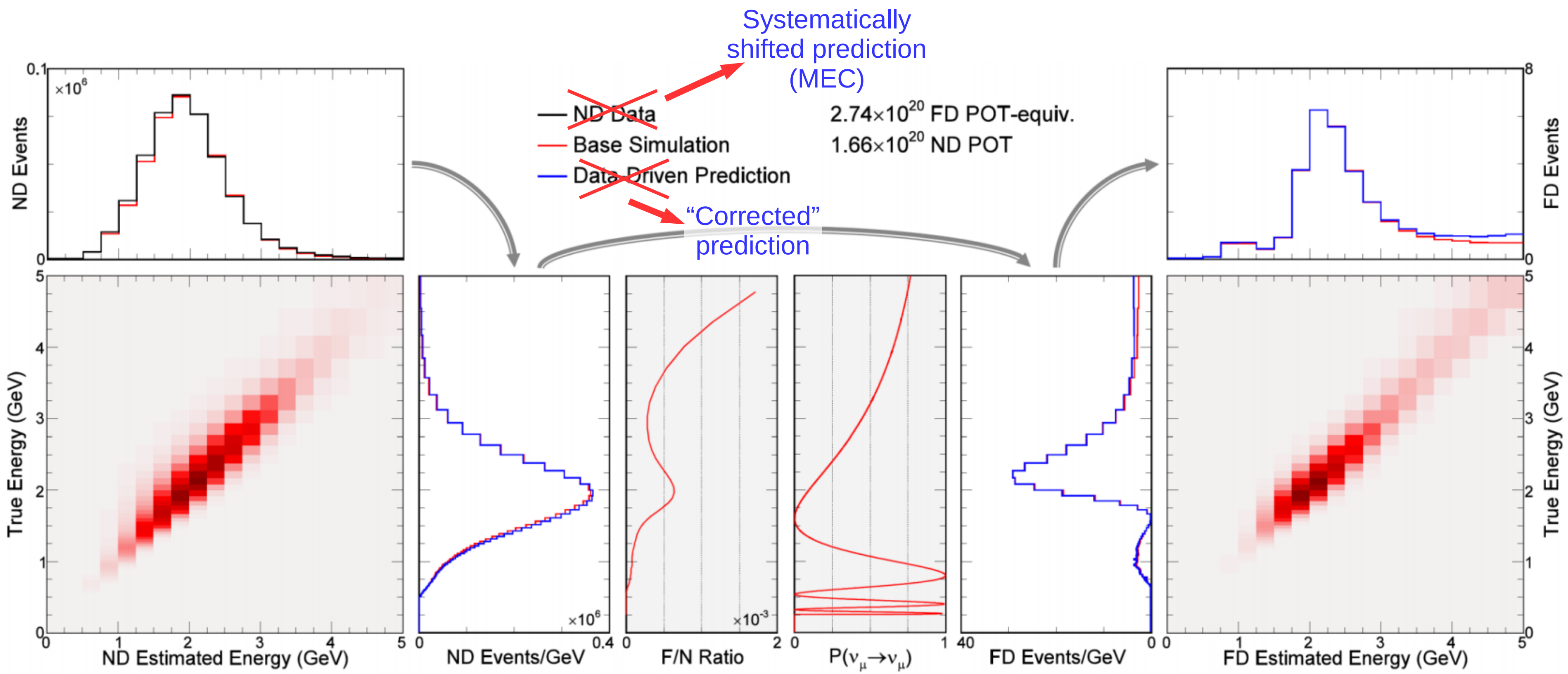
To examine the effect of extrapolation:



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

Testing extrapolation

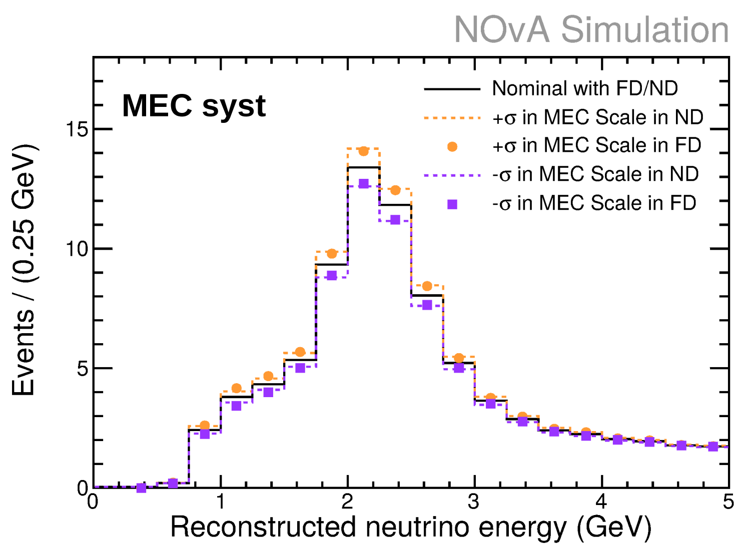
To examine the effect of extrapolation:



② Transport "corrected" prediction through extrapolation process

Testing extrapolation

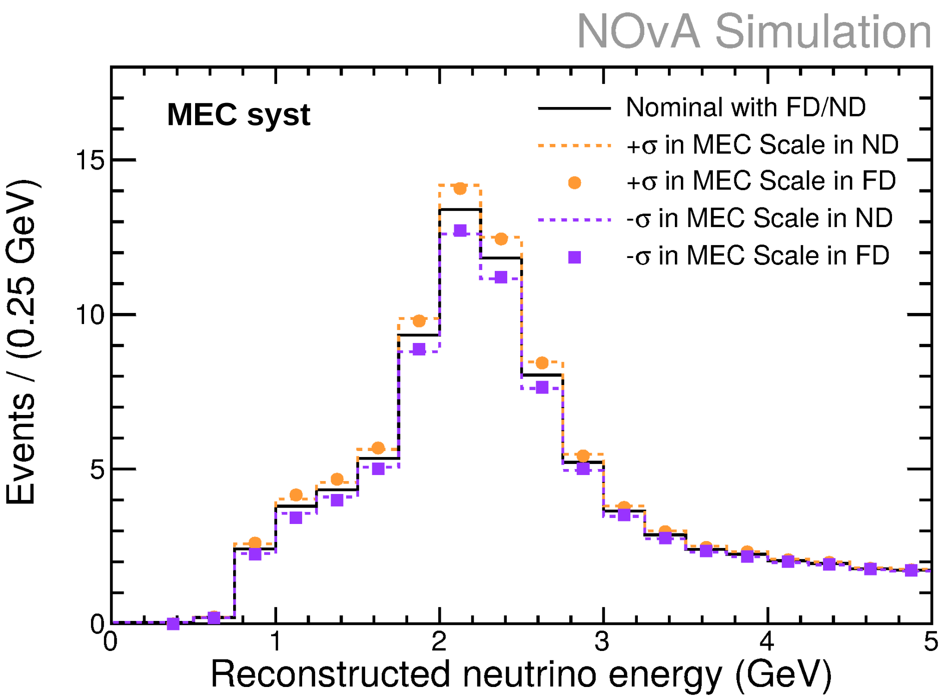
To examine the effect of extrapolation:

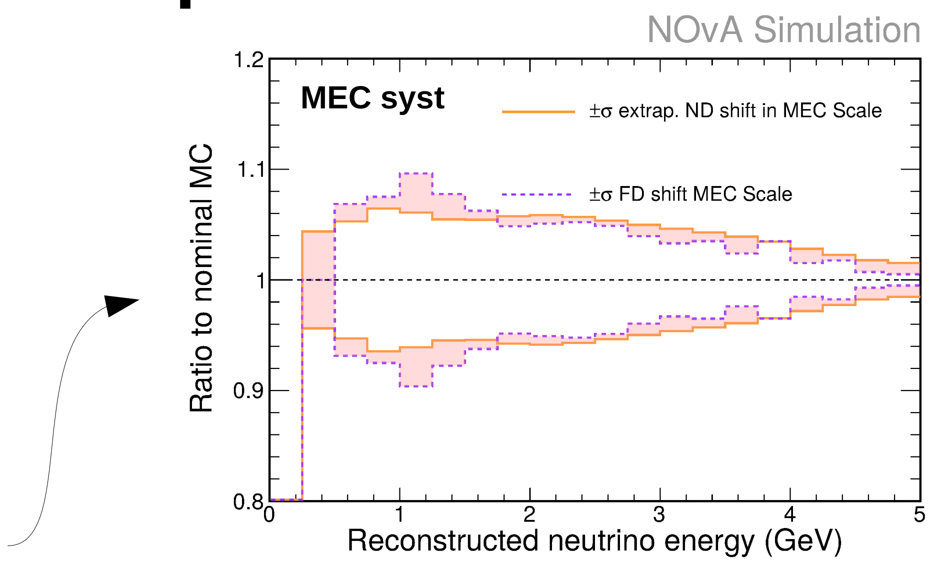


③ Compare “extrapolated” FD prediction to prediction obtained by varying FD directly.

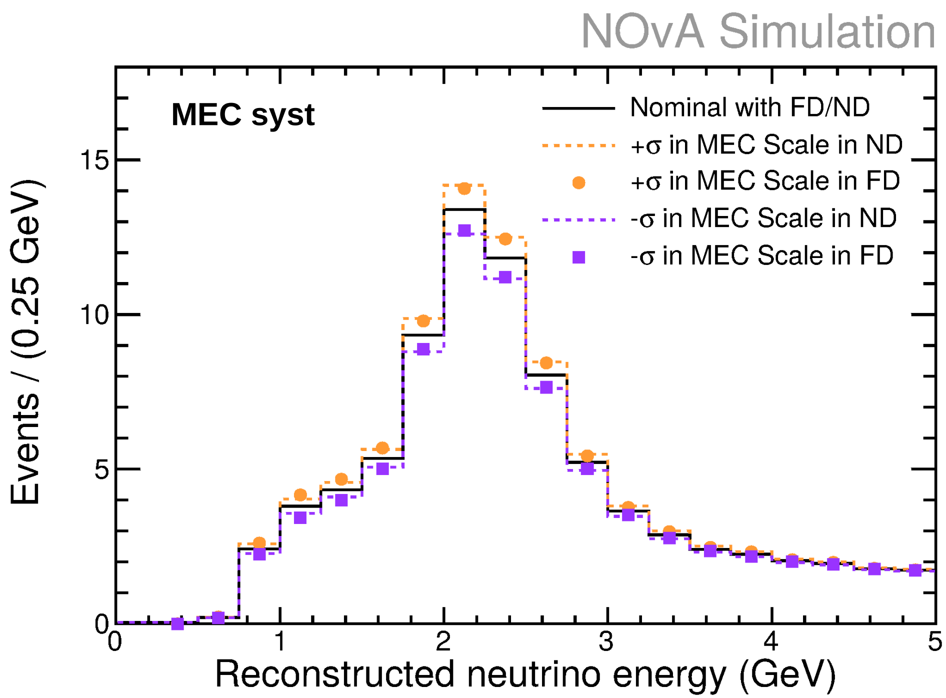
If they match, extrapolation perfectly accounts for the effect!

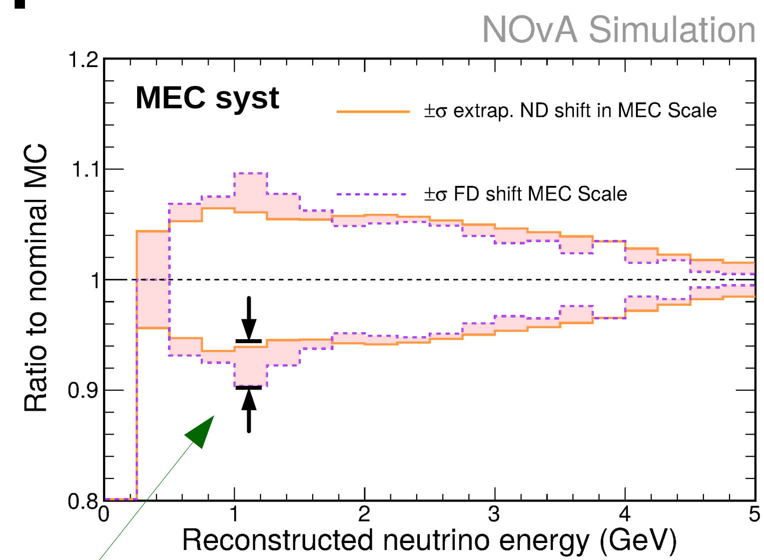
Testing extrapolation

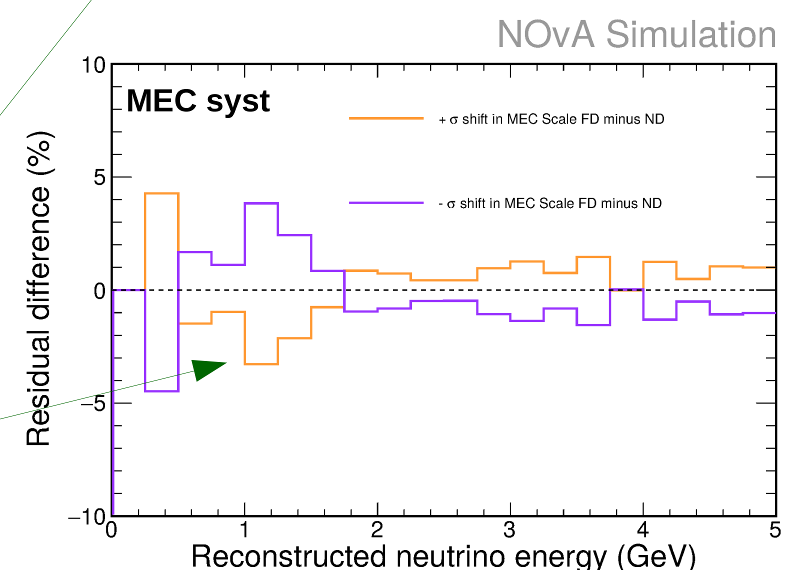




Testing extrapolation

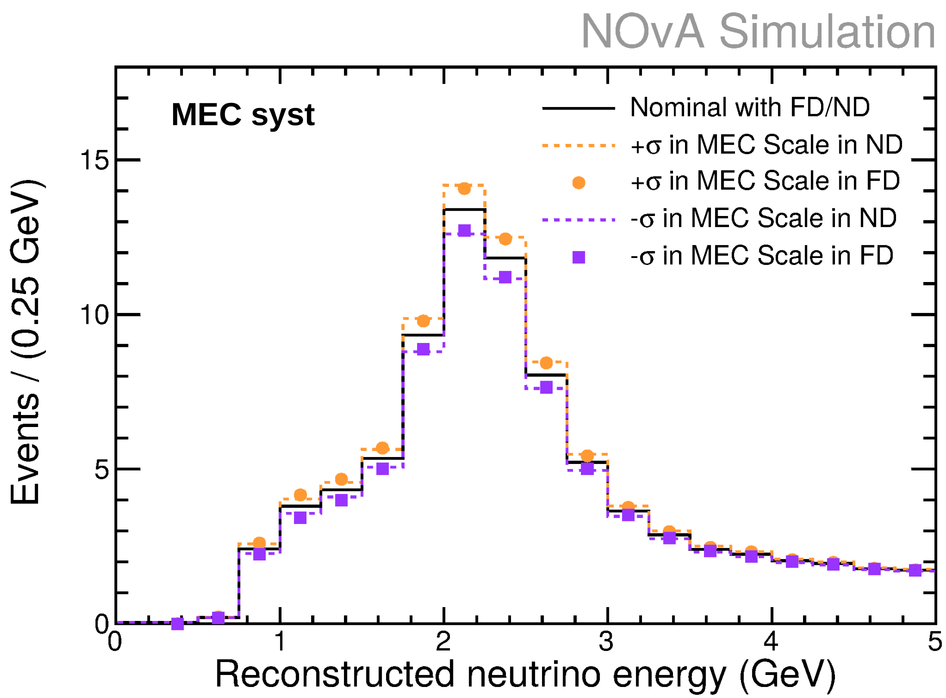


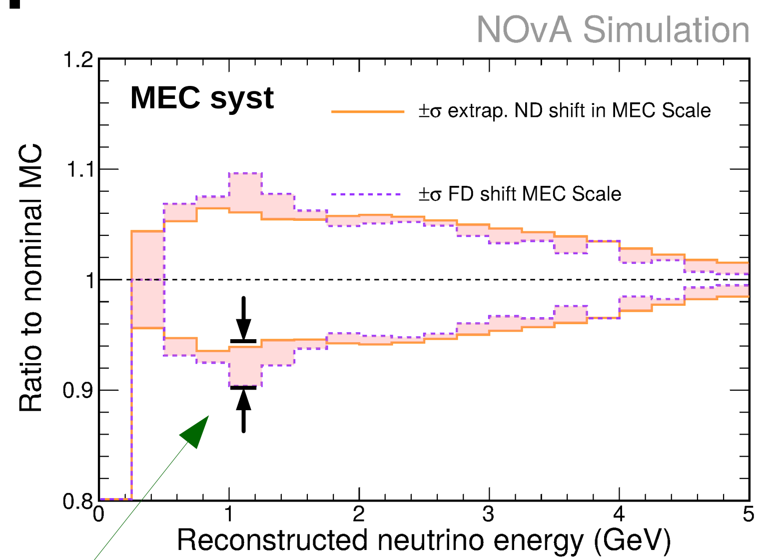


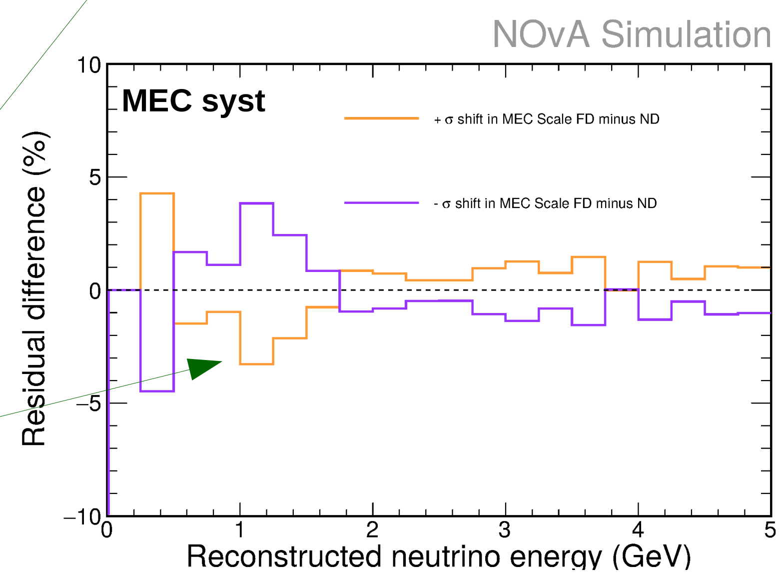


Only a few percent *residual* effect of MEC systs after extrapolation

Testing extrapolation



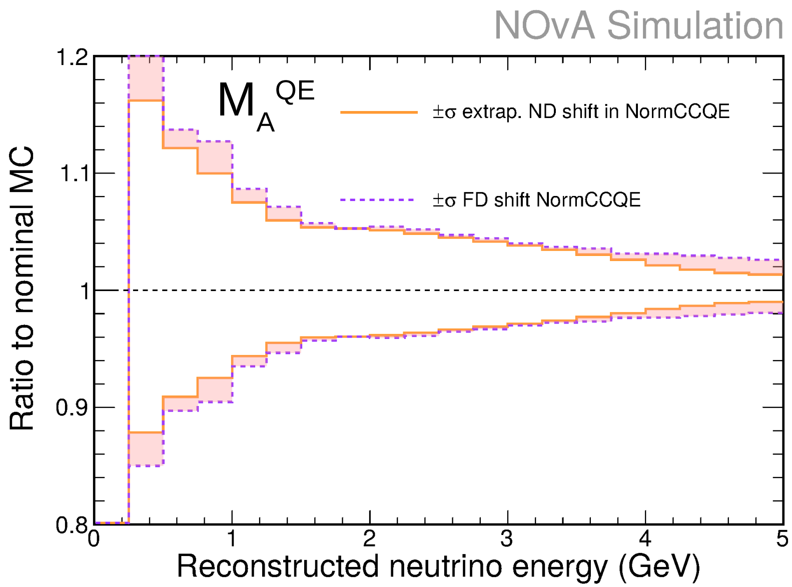


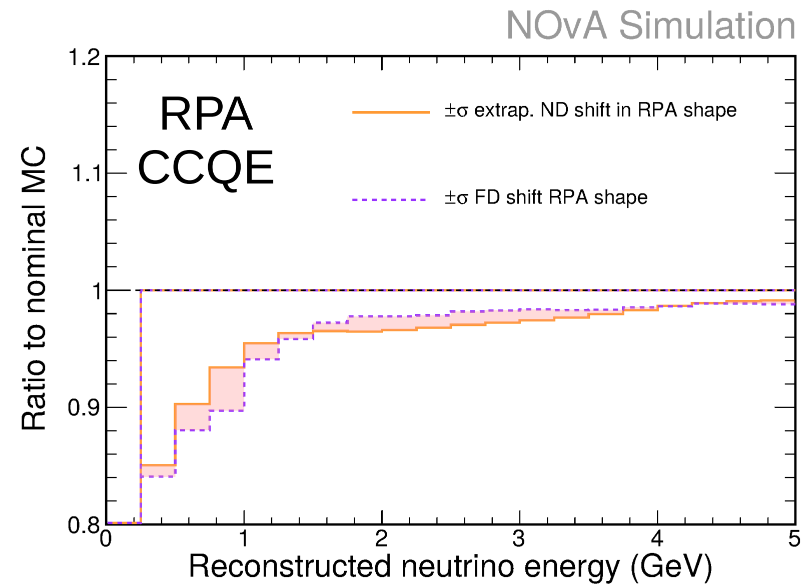


Only a few percent *residual* effect of MEC systs after extrapolation

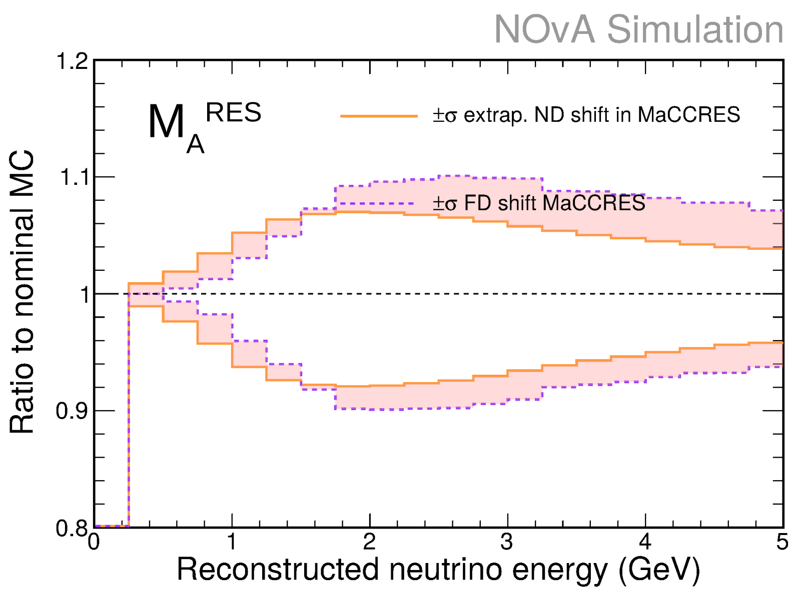
Though extrapolation procedure can't remove *all* effect of cross section uncertainties like MEC,
<u>extrapolation significantly reduces sensitivity to XS systs</u>

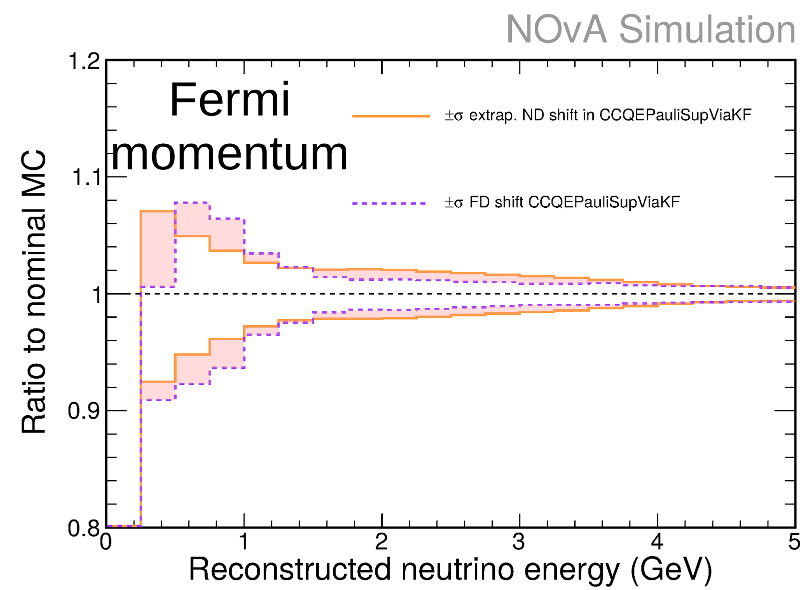
Other important XS uncertainties



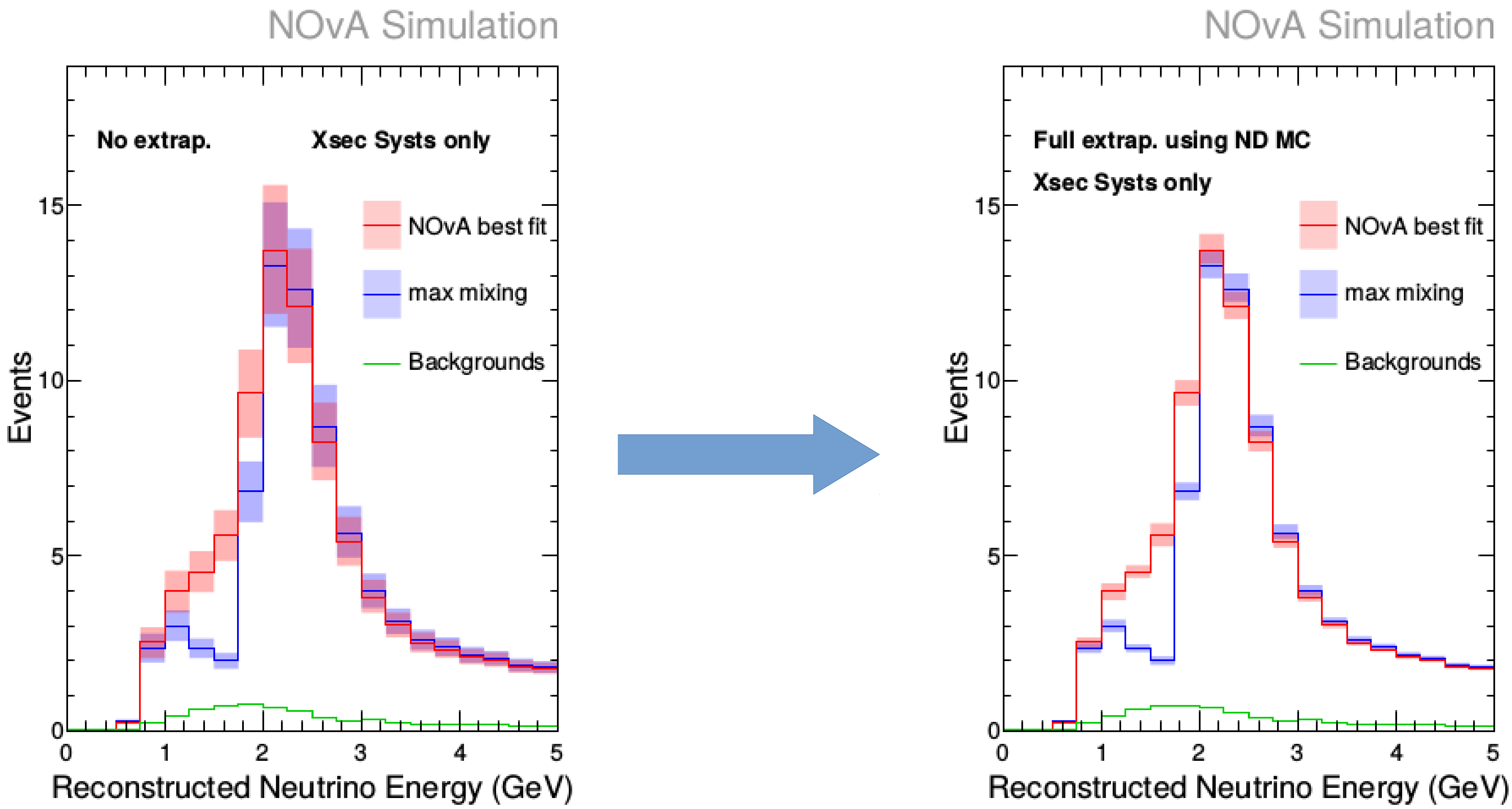


The story is similar for other important cross section uncertainties



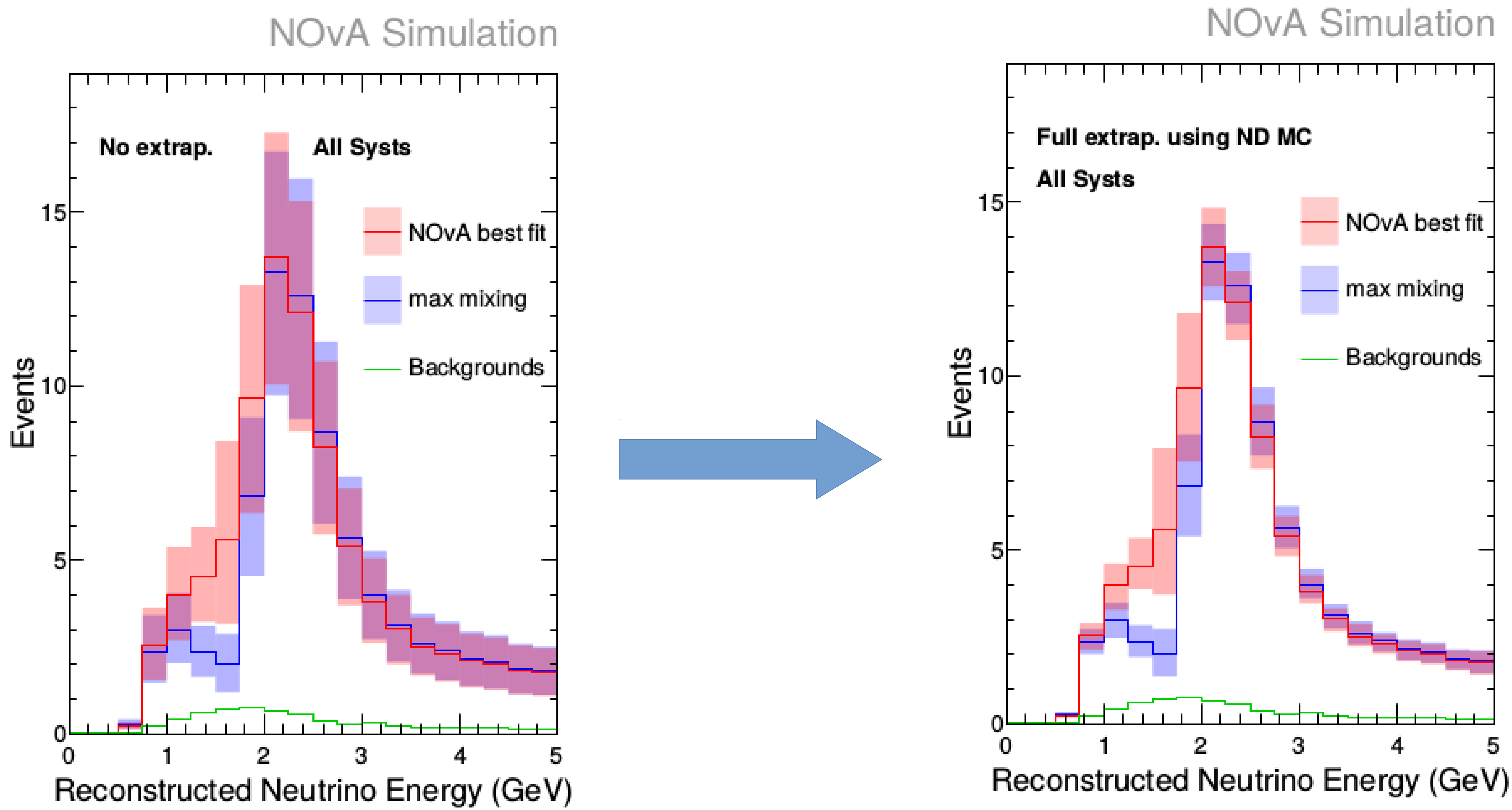


Extrapolation: all XS uncertainties



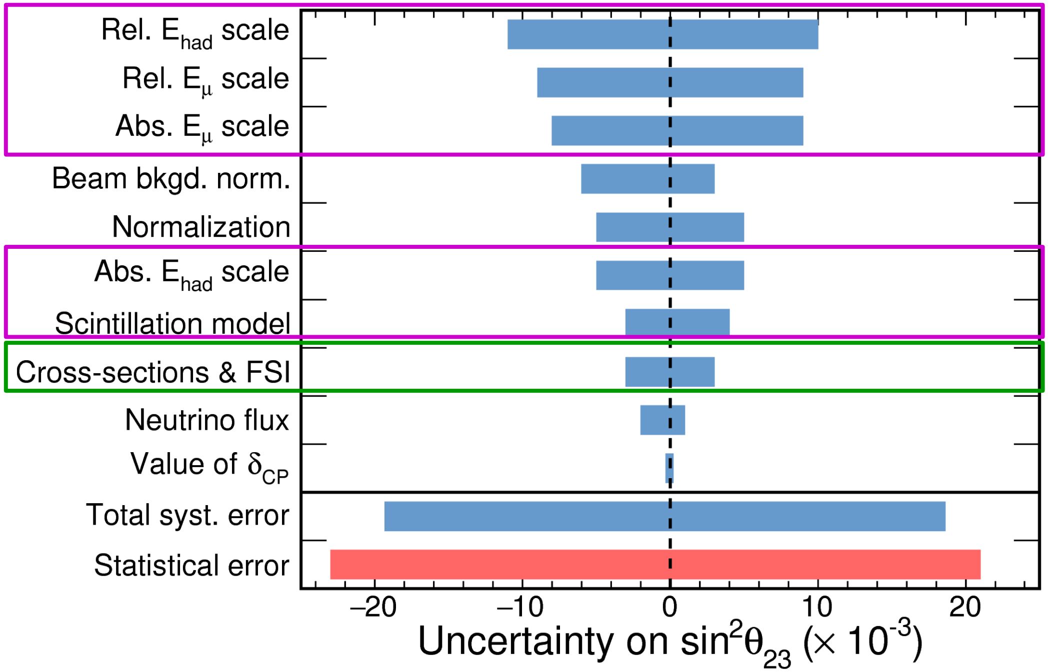
<u>Extrapolation *significantly* improves</u>
<u>the far detector prediction</u>,
even beyond the natural resiliency of the
detector design to XS systematics.

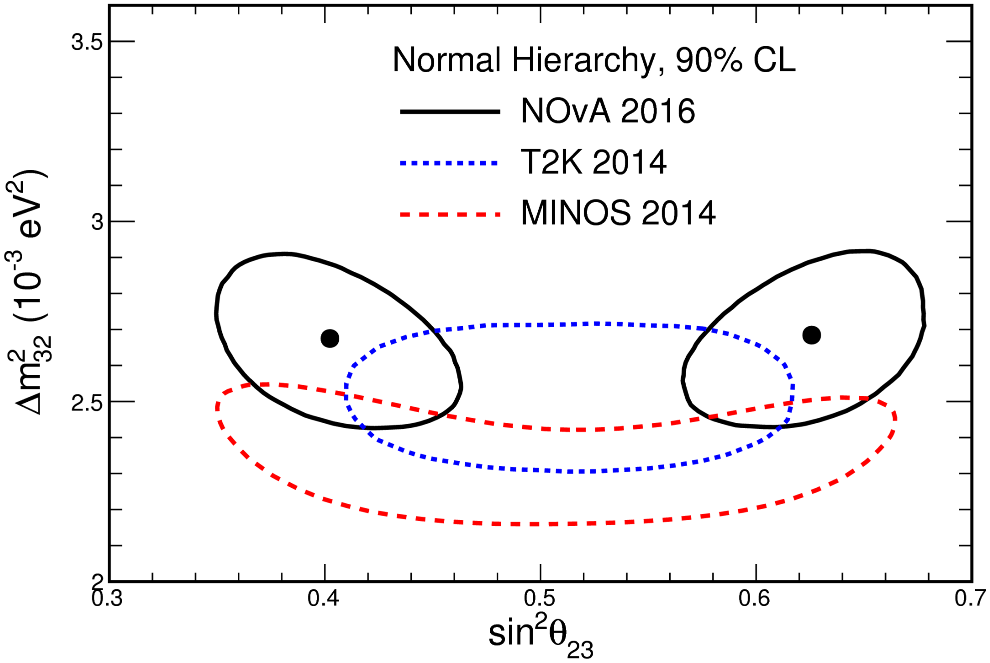
Extrapolation: all uncertainties



<u>Extrapolation *significantly* improves the far detector prediction</u>

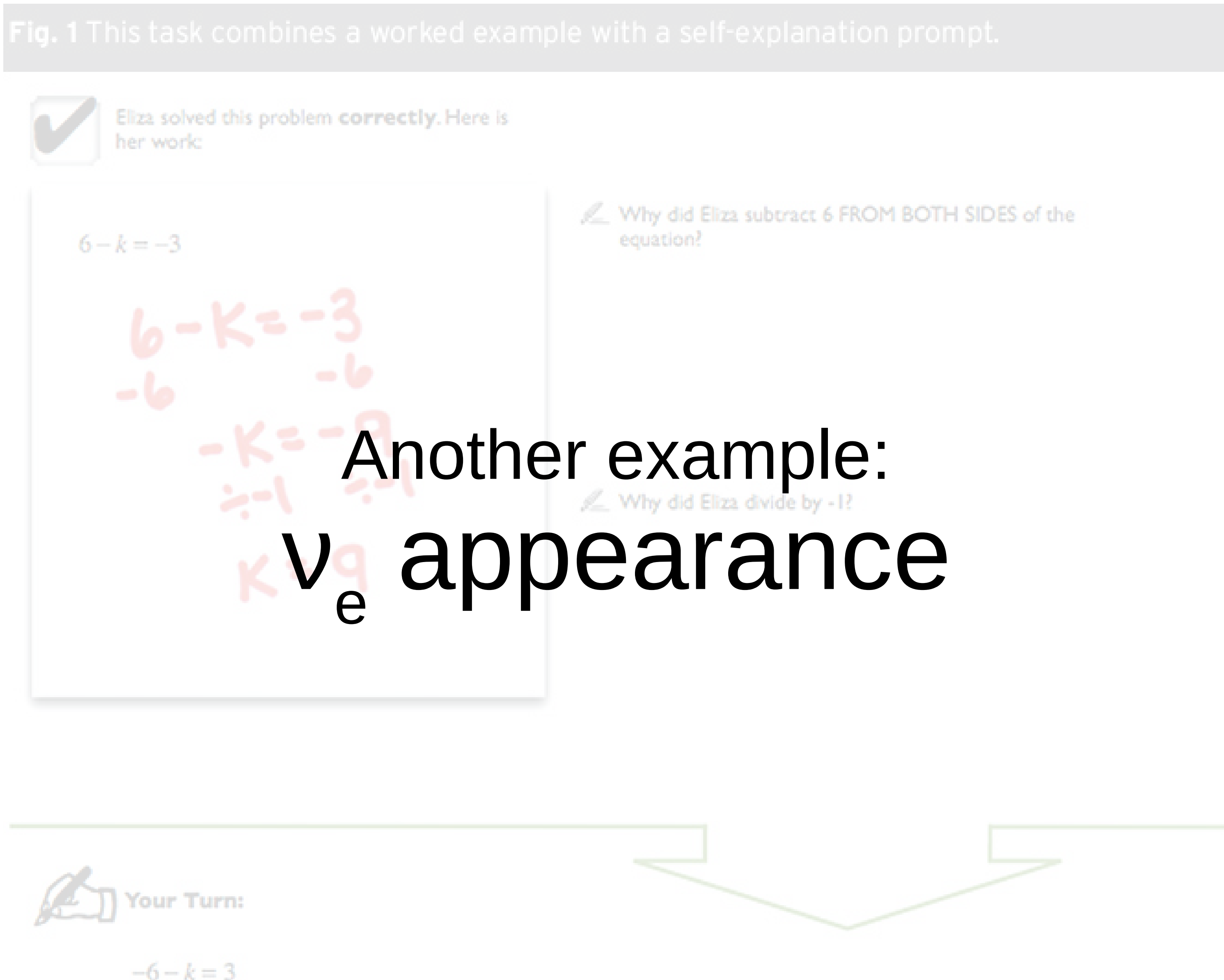
Effect on analysis





Cross section systematics are *subdominant* systematic uncertainties due to detector design & power of extrapolation.

Strength of NOvA results driven by understanding of detector response, not cross sections.
(More important for Δm^2, but same story holds.)



Another example:

ν_e appearance

ν_e appearance

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

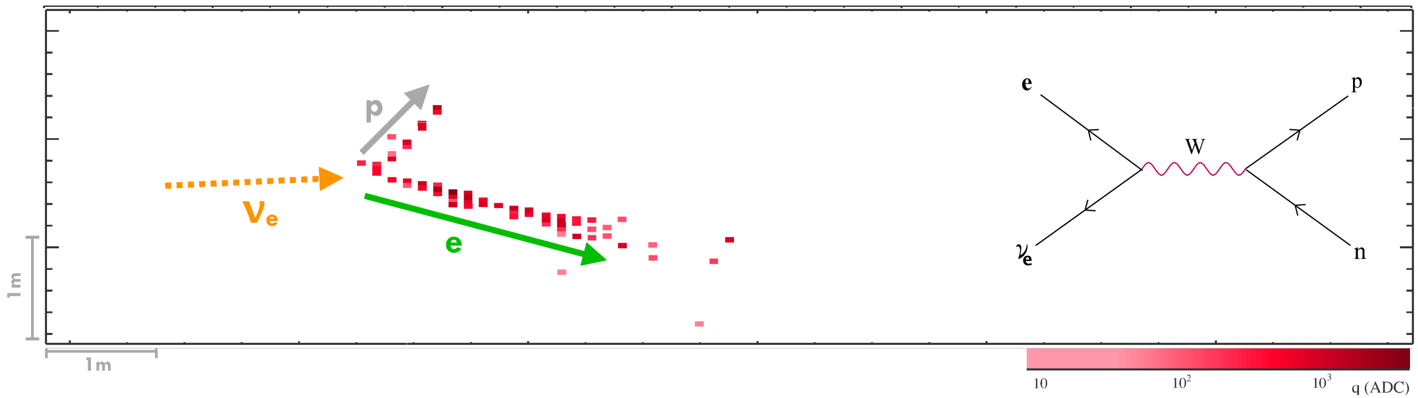
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

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

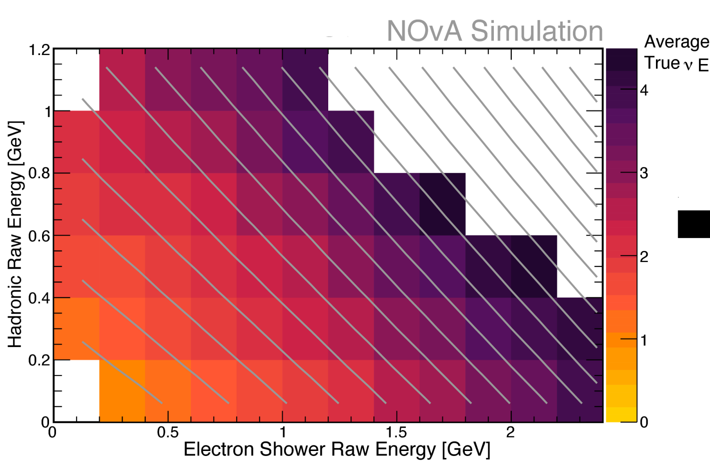
Where: $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\Delta = \Delta m^2_{31} \frac{L}{4E}$ $A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$

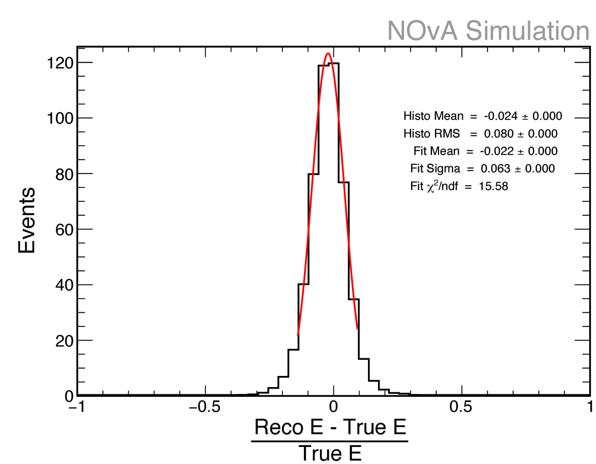
Besides the dependence on the mixing parameters, we learn about the mass ordering (via α) and δ_{CP}

ν_e appearance: selection & reconstruction



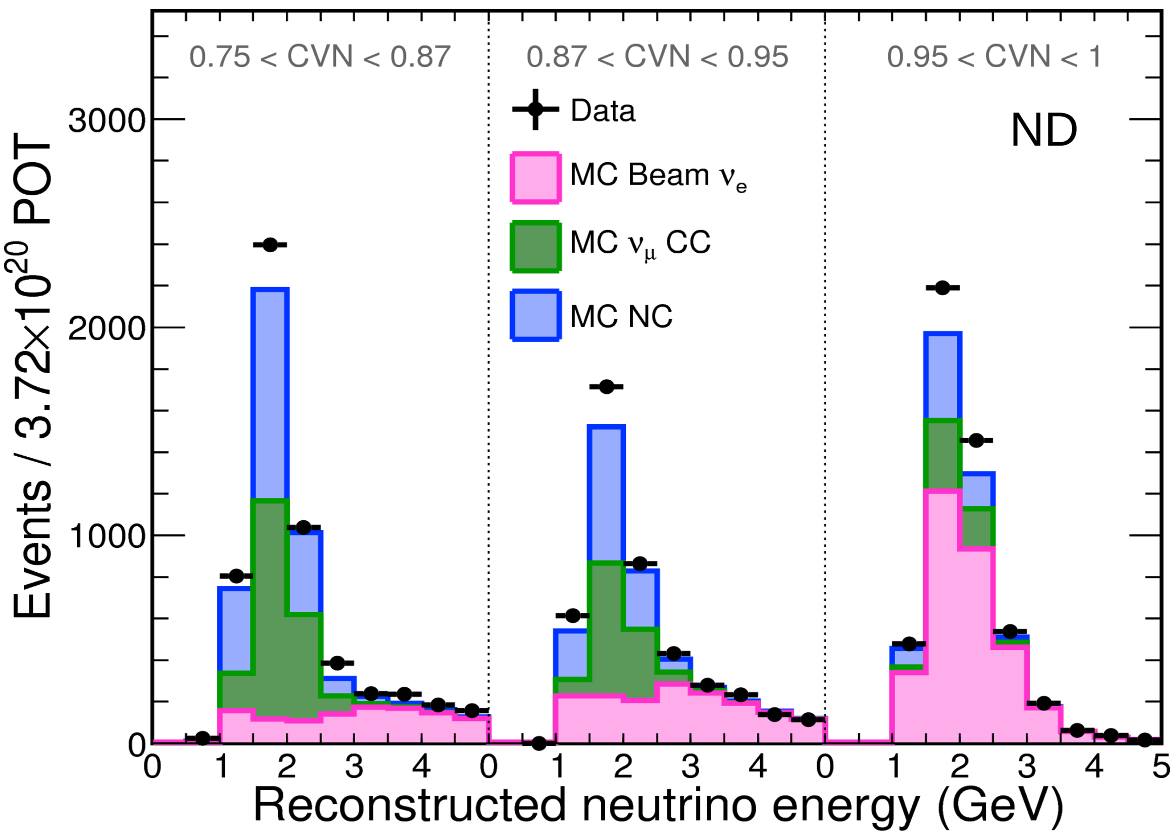
Convolutional neural network selects events via transformations applied to energy deposits treated as images





Energy estimator is quadratic function of E_e and E_{had}.
~8% resolution

ν_e appearance



Least ν_e-like → Most ν_e-like

(Divided into bins of event classifier)

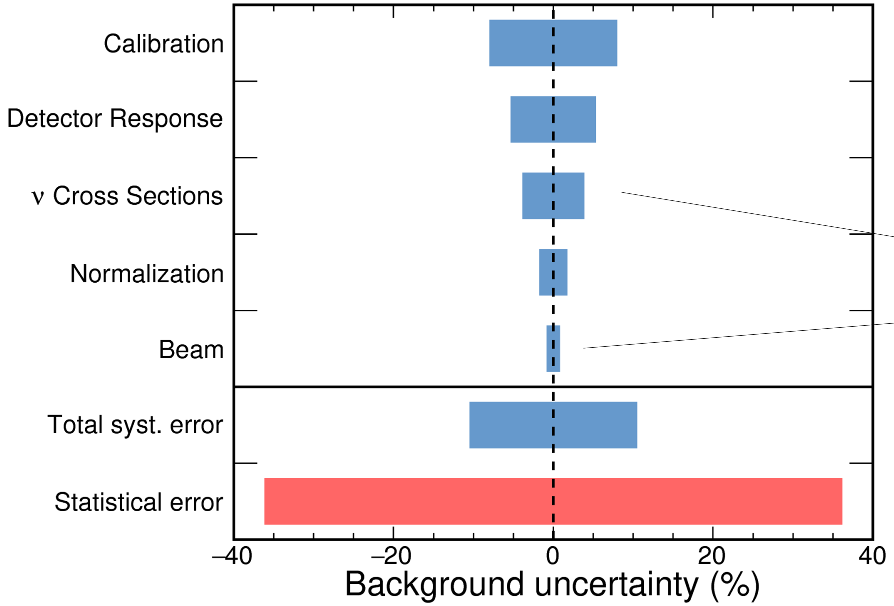
Added challenges:

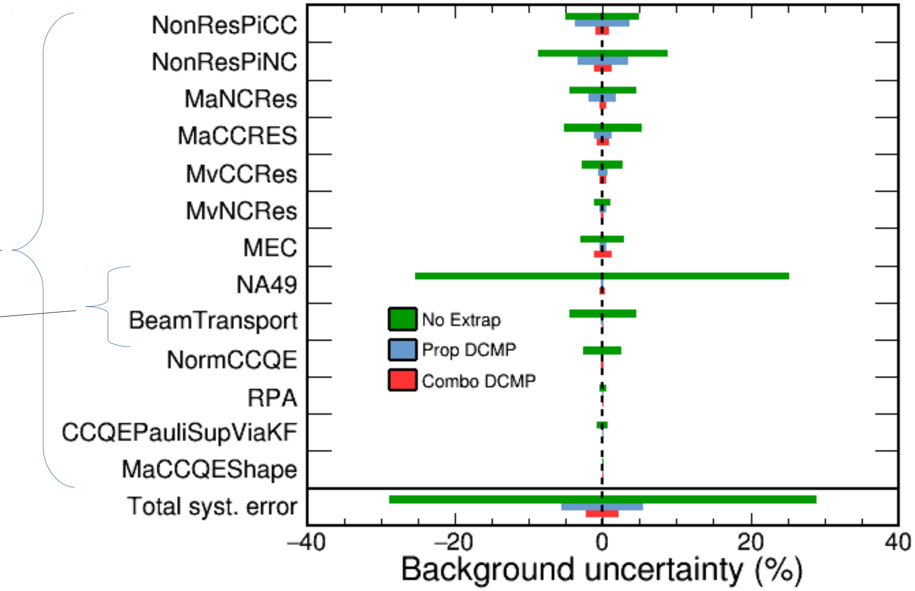
- **Significant backgrounds which oscillate differently**
  - **Beam ν_e** oscillate very little over this L/E
  - **ν_μ** almost entirely disappear
  - **NC** doesn't change due to oscillations (assume no steriles)

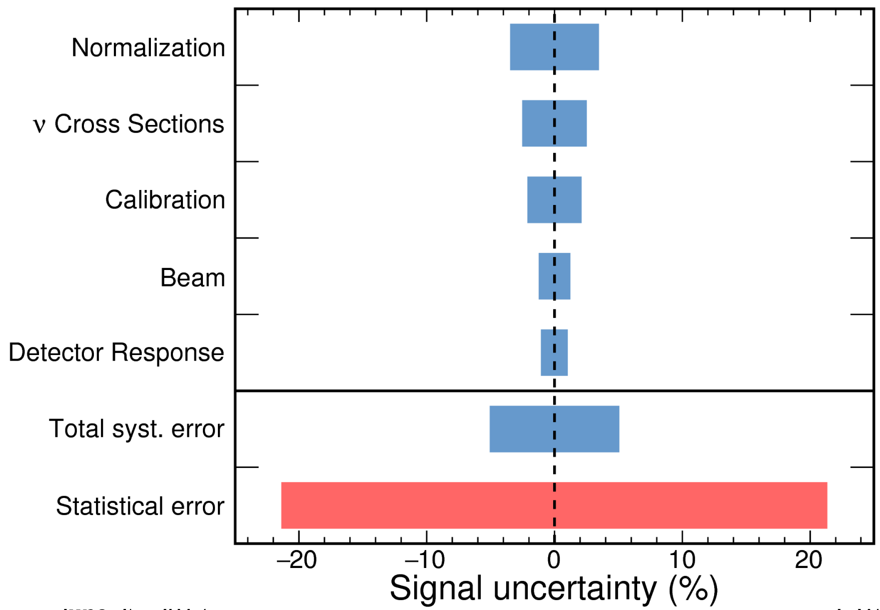
Need to disentangle ("decompose") before applying Far/Near makes any sense.

- **No signal at ND**
  - And difference ν_μ ND vs. ν_e FD acceptance

ν_e appearance



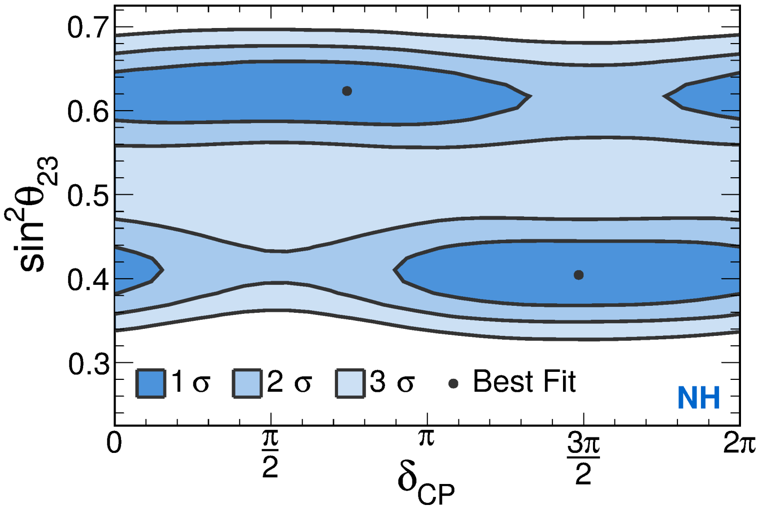


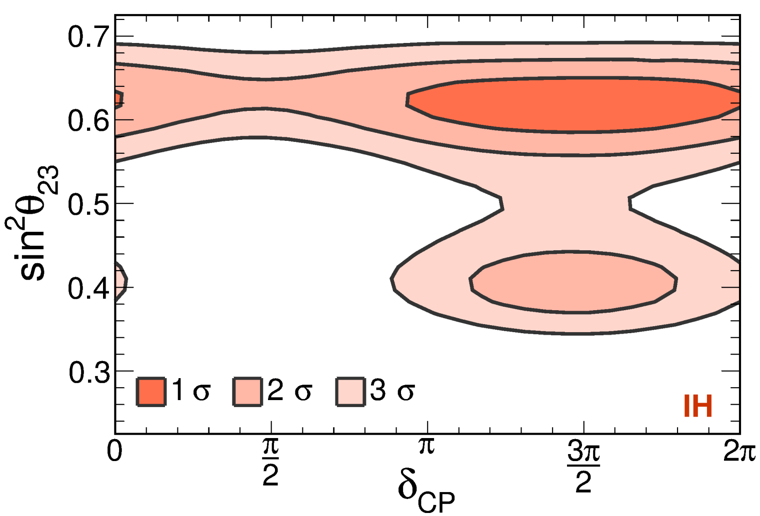


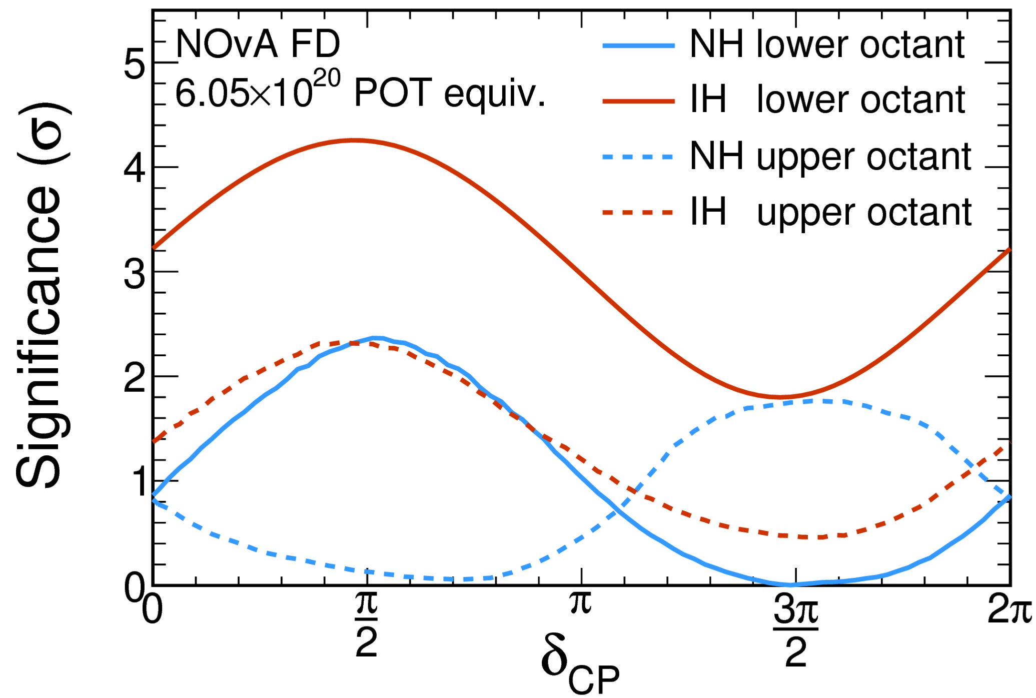
Cross section systematics more important for signal here, but still under control for now.

We expect to continue to benefit from ongoing work by this audience (and others) as well, to keep them that way...

ν_e appearance







(joint fit w/ ν_μ disappearance)

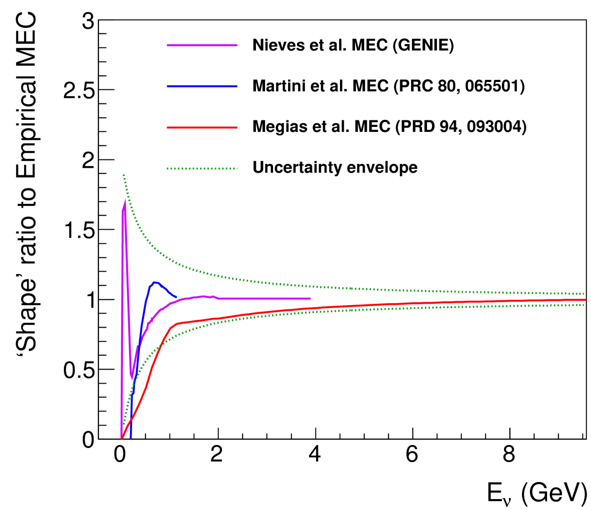
Cross section uncertainties: future

- Continue working on updating XS uncertainty budget in light of recent developments
  - Introduction of MEC & assoc. errors affects QE uncertainties:
    - Reduce GENIE M_A^{QE} towards bubble chamber measurements (~5%, instead of ~25%)
    - Or, better, consider switching to z-expansion uncertainties since dipole is poor *ansatz*
  - RPA correction to GENIE QE: following Valencia treatment via R. Gran (arXiv:1705.02932)
  - Following world resonance-dominated pion production measurements closely (M_A^{RES}, etc.)
  - Transition-region soft DIS since ANL-BNL resolution & retuning (Eur. J. Phys C76, 474)
  - ν_e XS relative to ν_μ (Phys. Rev. D86, 053003)
  - Further inspection of non-reweightable GENIE uncertainties (hadronization, etc.)
- In the process of binding *alternate generators* (NEUT, GiBUU) to NOvA software framework to study impact of models not in GENIE
- NOvA XS measurements will enter as constraints once they are ready!

Cross section uncertainties: future (MEC)

Want **robust uncertainties** to cover (potential) differences from Empirical MEC:

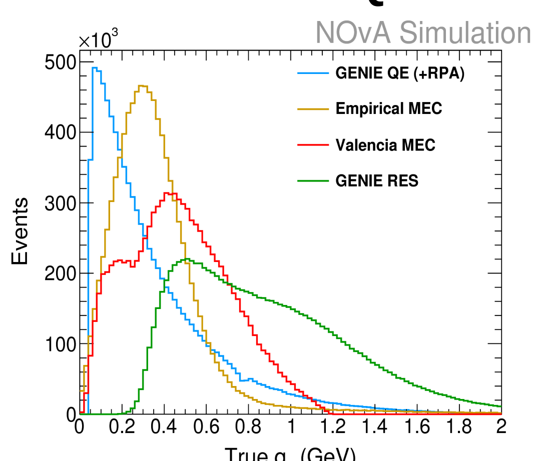
1. **Bound $\sigma_{MEC}(E_\nu)$ shape by comparing EmpMEC to other models**

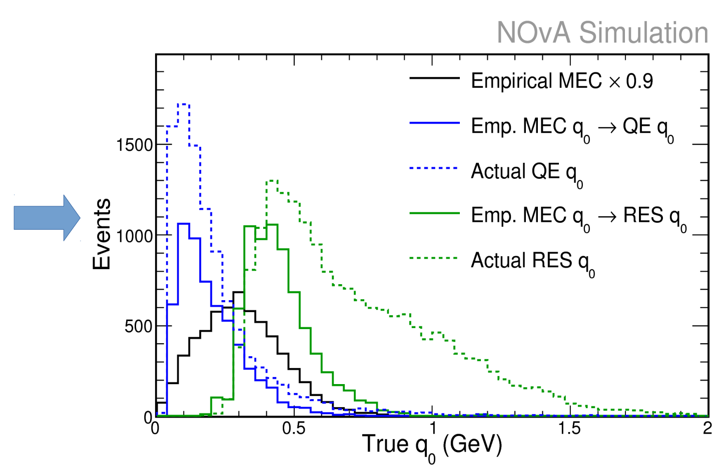


2. **Bound nn-np initial state ratio by comparing predictions from models** (València via GENIE, SuSA-MEC via *PRC**94**, 054610*)

$$0.7 \le \frac{np}{(np+nn)} \le 0.9$$

3. **Bound q_0 shape by reweighting Empirical MEC to GENIE QE and RES**





Summary

- NOvA relies on **strong internal constraints** on cross section uncertainties for its rich physics program
  - Calorimeter design minimizes *a priori* impact
  - Dual, functionally-identical detectors enable major cancellation of residual errors in oscillation analyses
- Comprehensive program underway to ensure all **relevant cross section issues are considered**
- **Current antineutrino run** will enable even more interesting oscillation and cross section measurements
- Expect **updated oscillation results** (with updated cross section uncertainties) later this year!

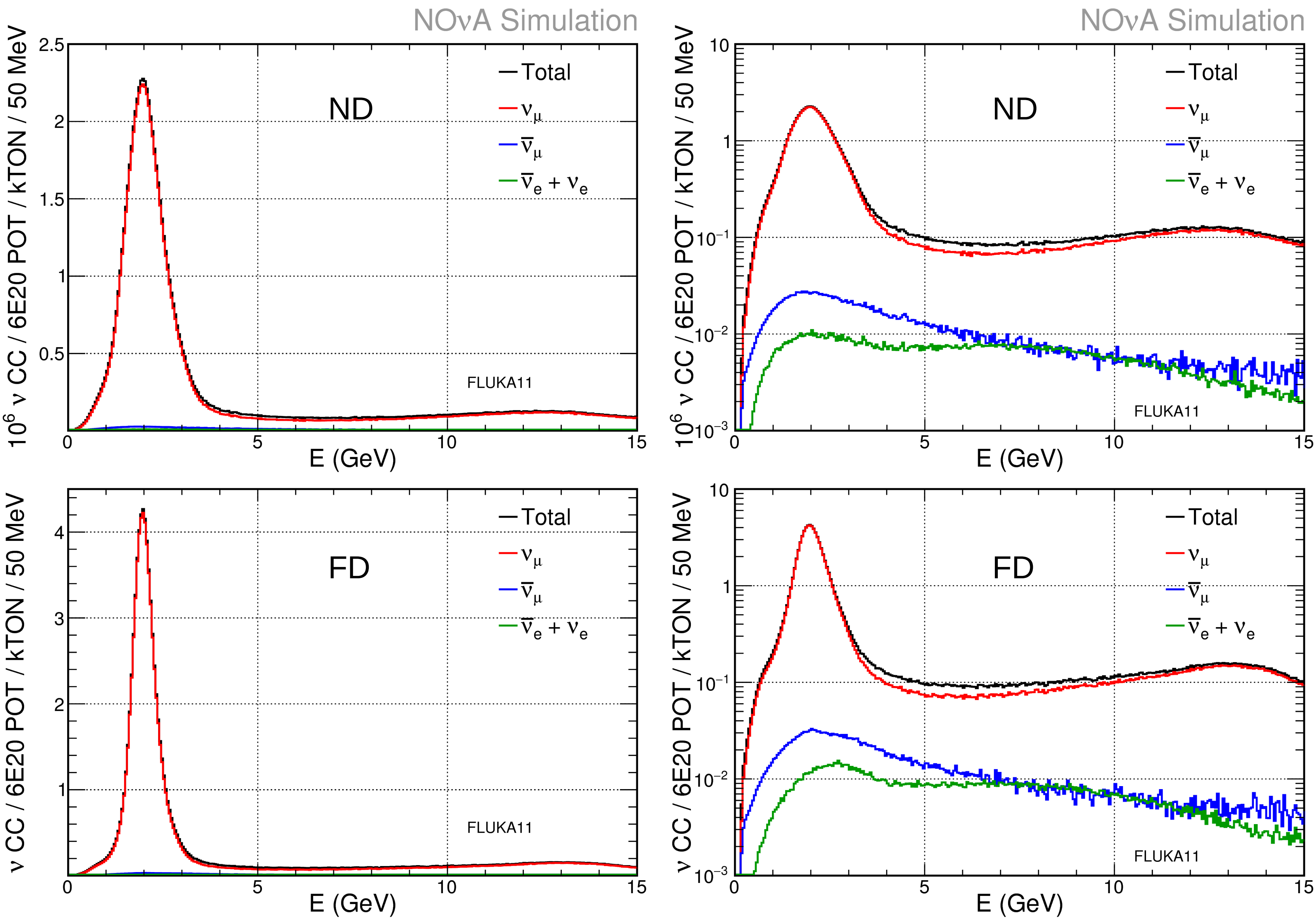
Other NOvA talks at NuInt 2017:

Inclusive numu and nue CC measurements at NOvA	*Jonathon PALEY*
230, Fields Insitute	**Monday**, June 26, 10:20 - 10:45
The NuMI Flux Prediction	*Leonidas ALIAGA SOPLIN*
230, Fields Insitute	**Monday**, June 26, 14:20 - 14:45
Pion production measurements at NOvA	*Hongyue DUYANG*
230, Fields Insitute	**Tuesday**, June 27, 16:15 - 16:35

Thank you on behalf of NOvA!

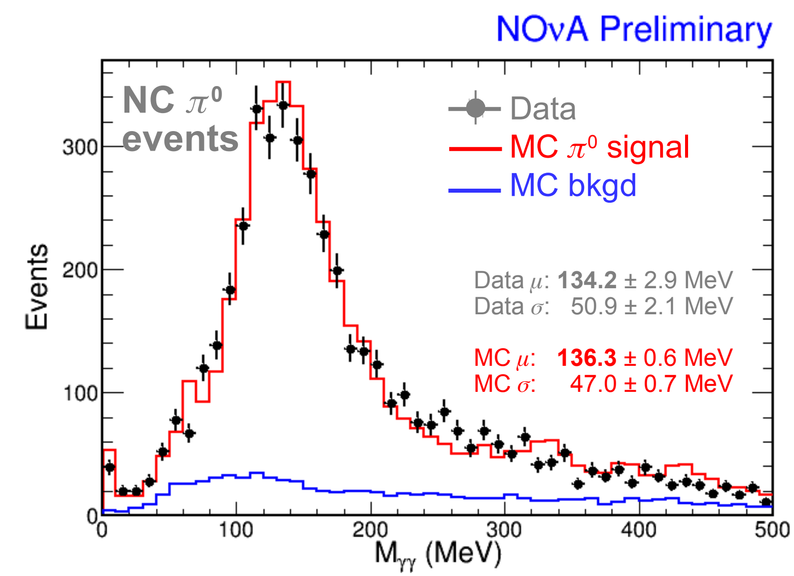
Overflow

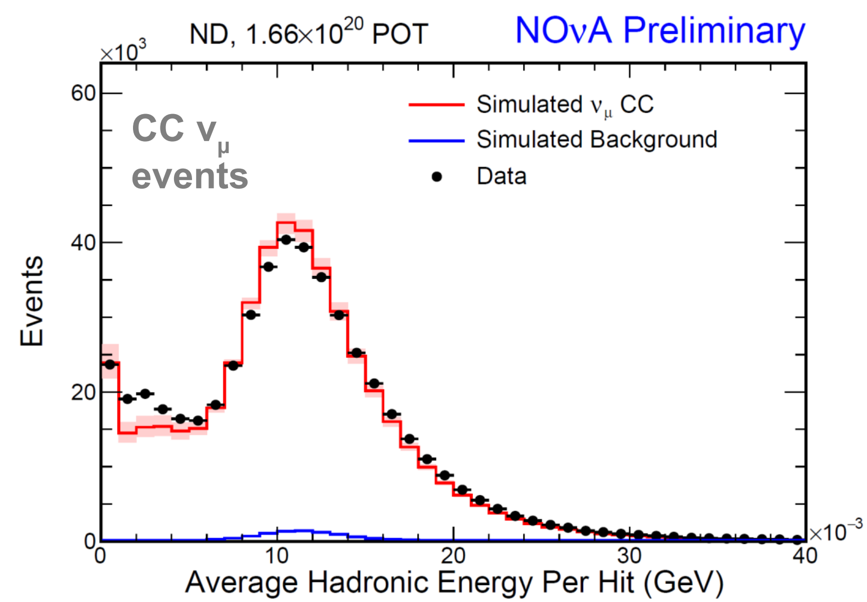
Beam spectral shape



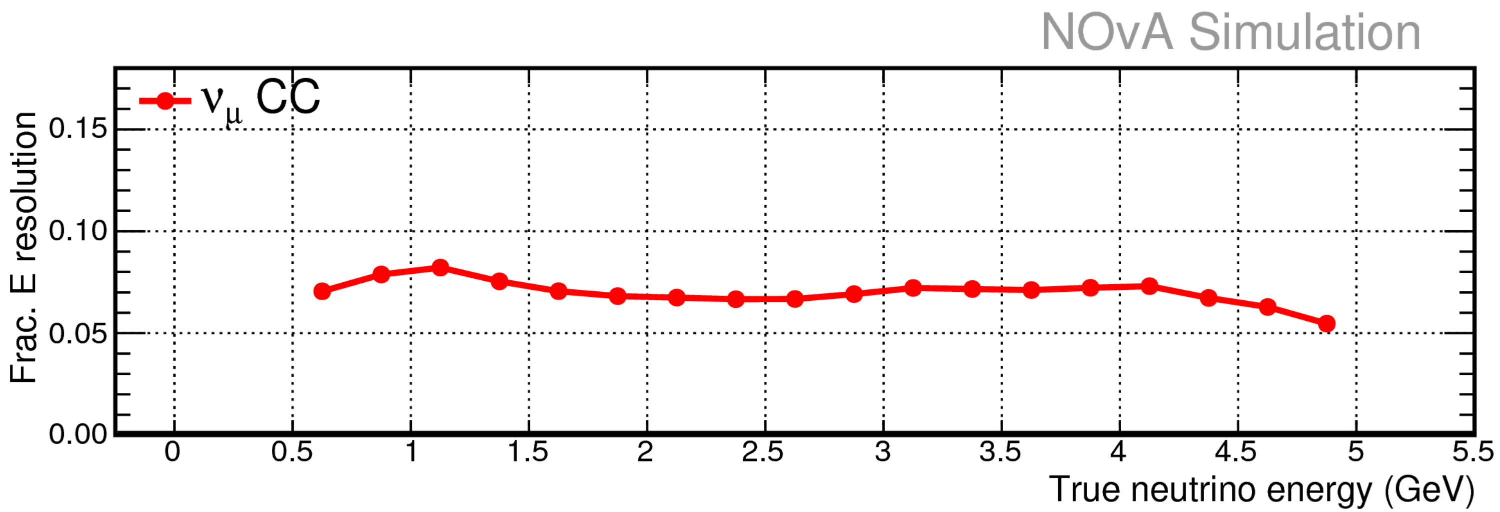
Fixing the energy scale

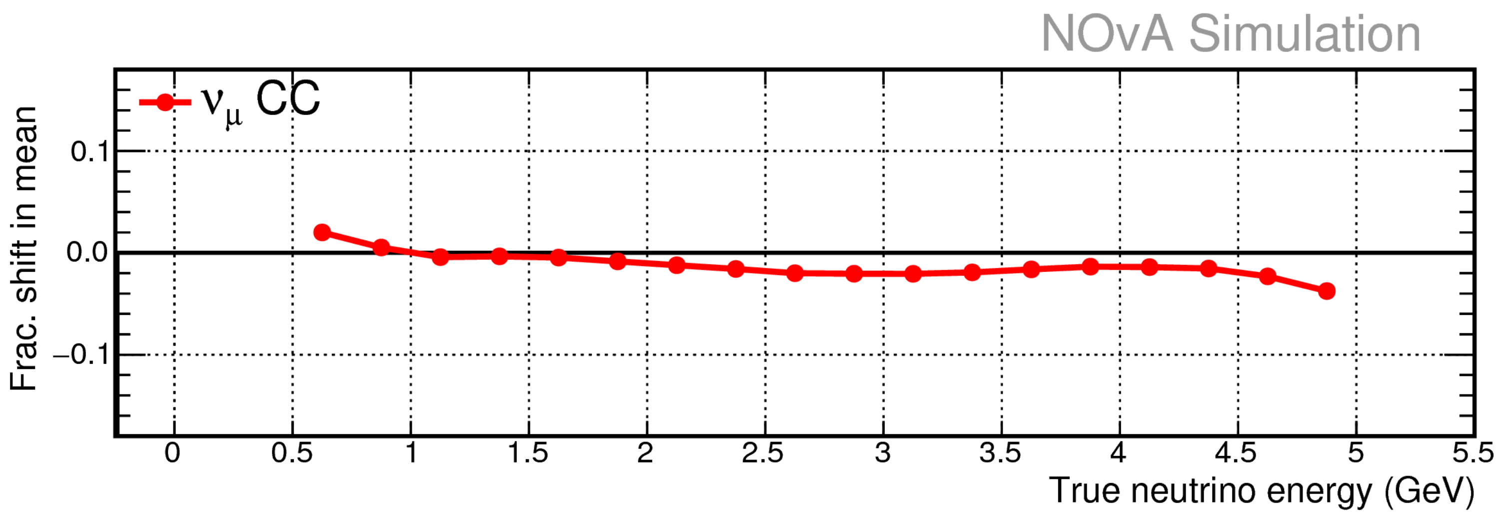
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
  - π^0 mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
- All agree to 5%



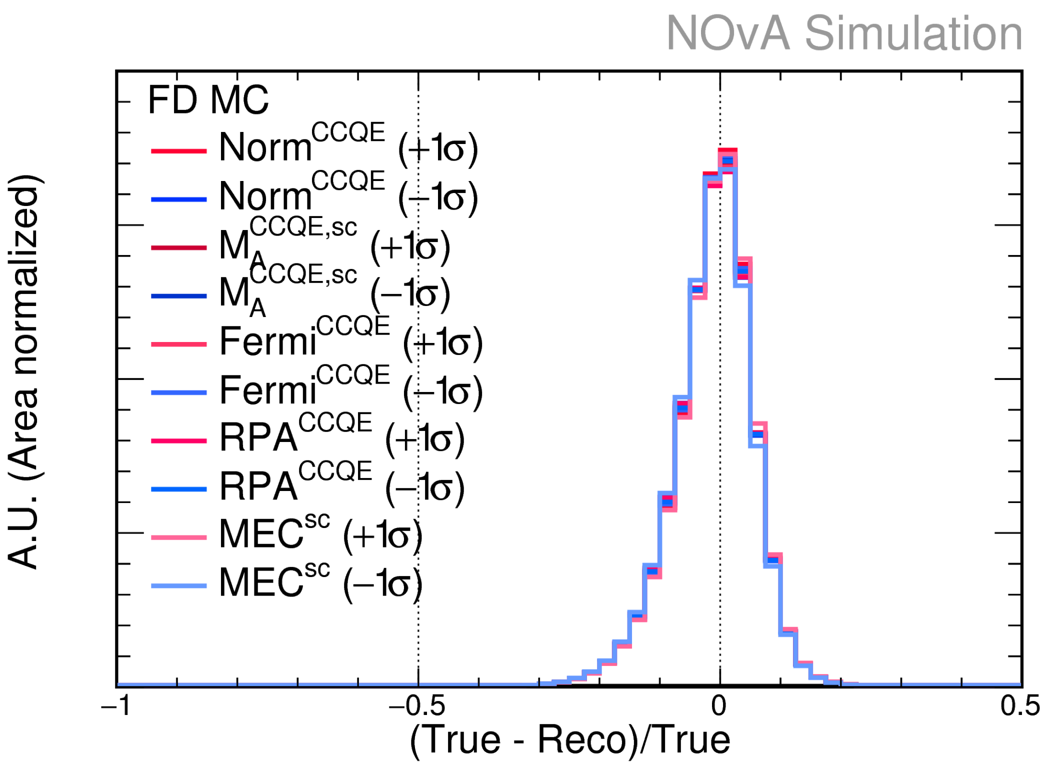


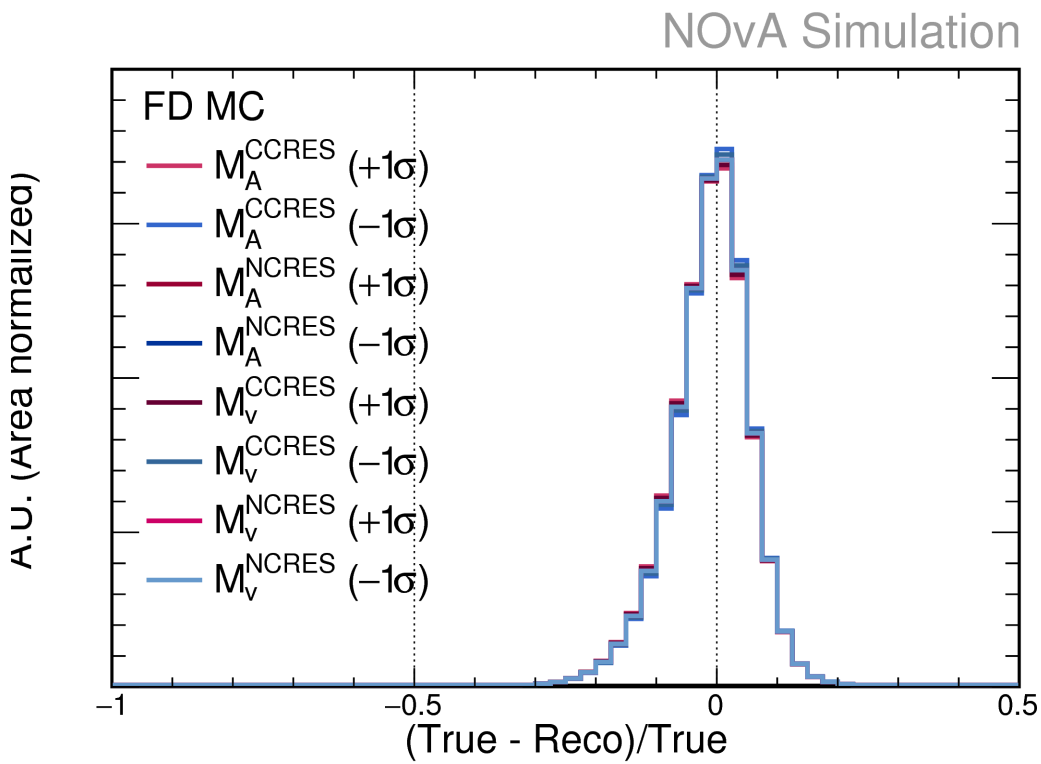
ν_μ disappearance: energy resolution



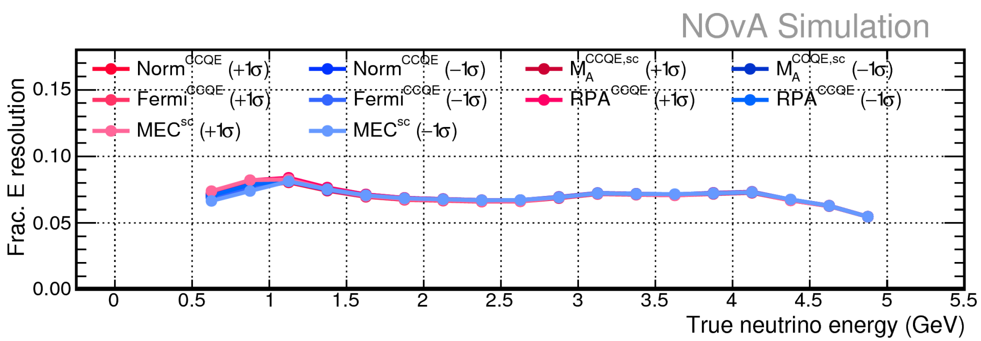


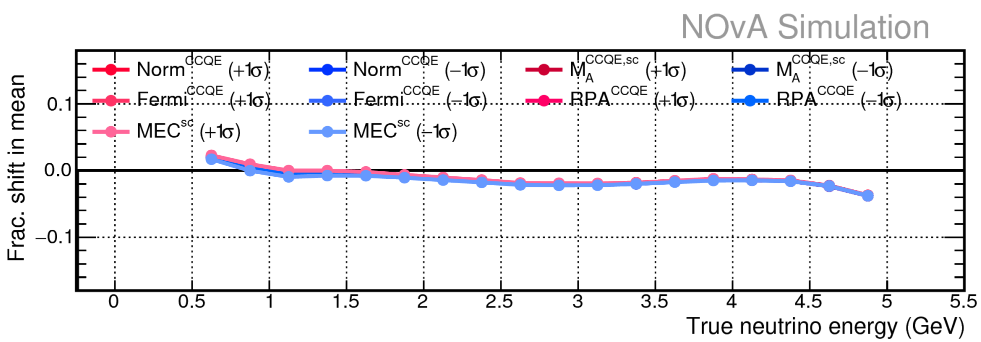
ν_μ disappearance: energy resolution





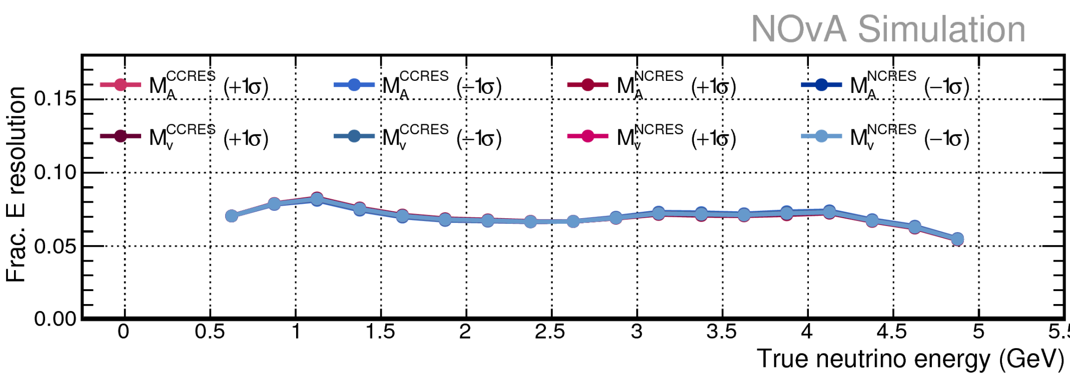
ν_μ disappearance: energy resolution

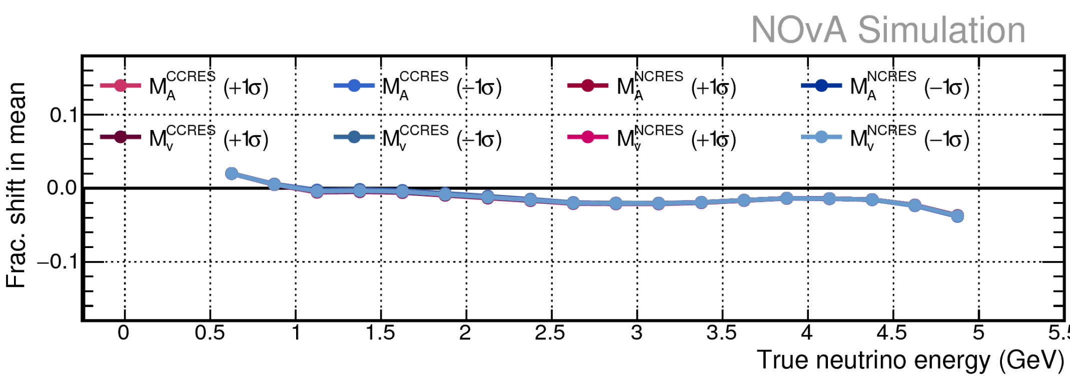




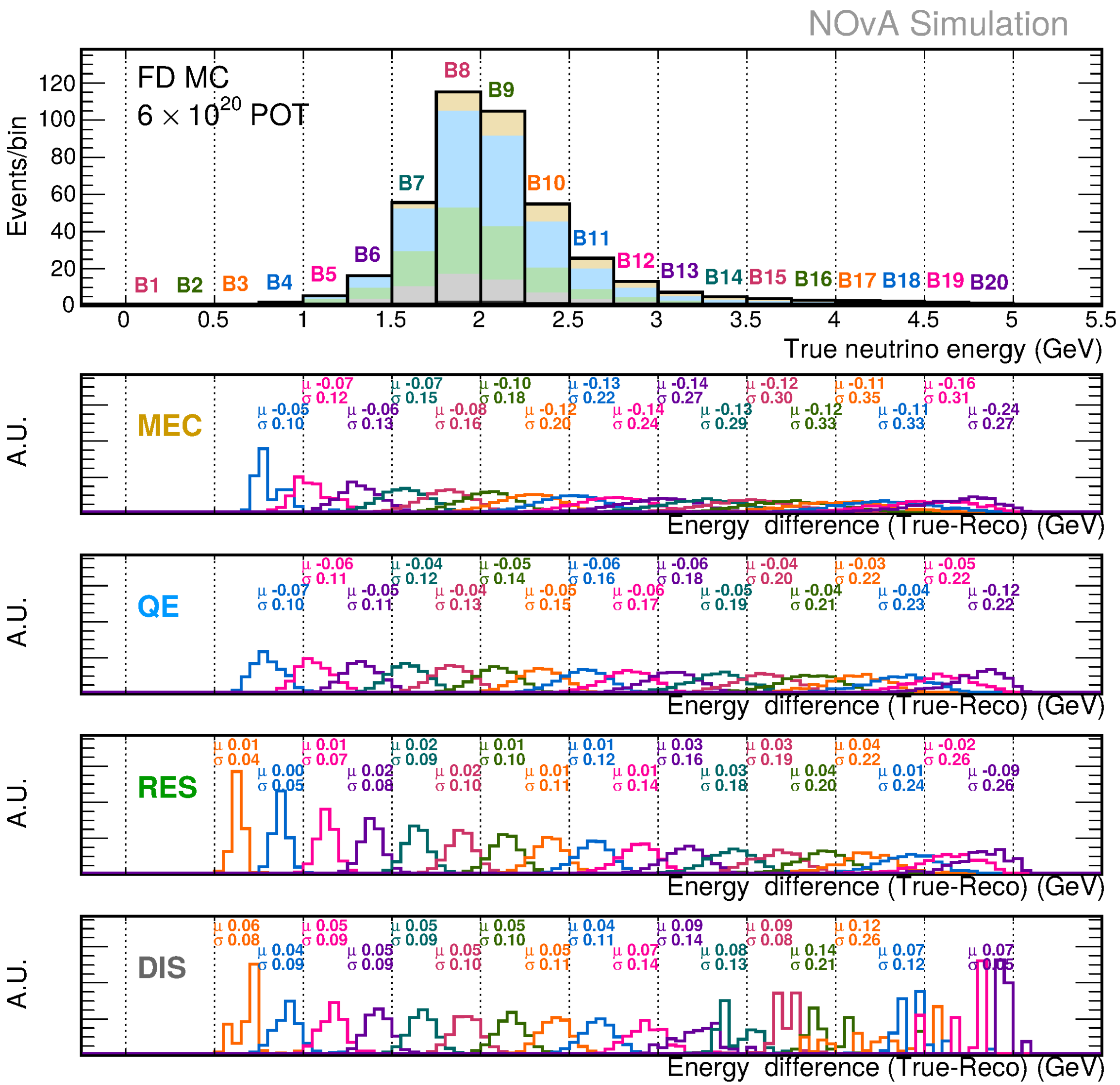
XSec Systs set #1

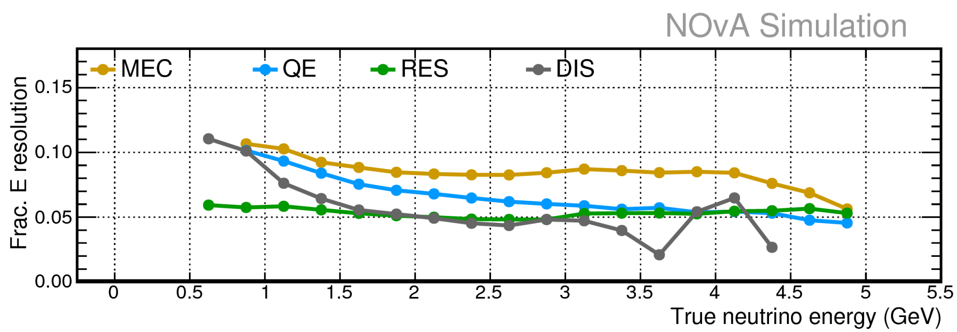
XSec Systs set #2

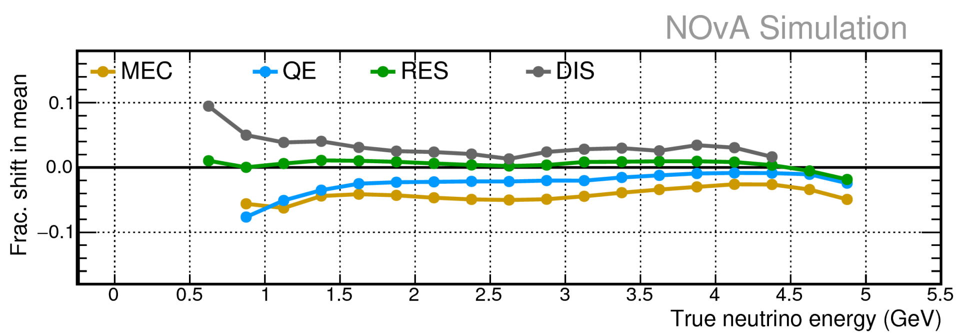




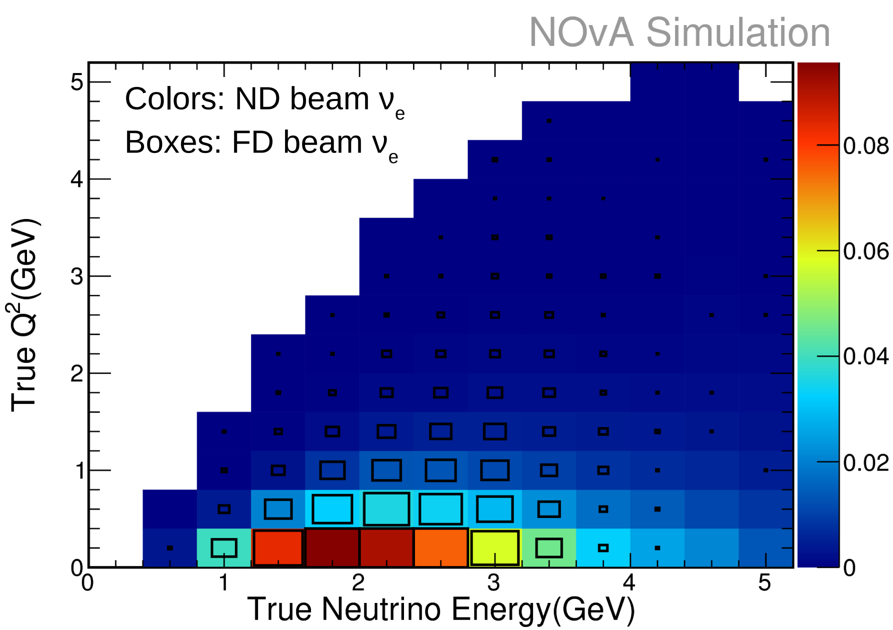
ν_μ disappearance: energy resolution

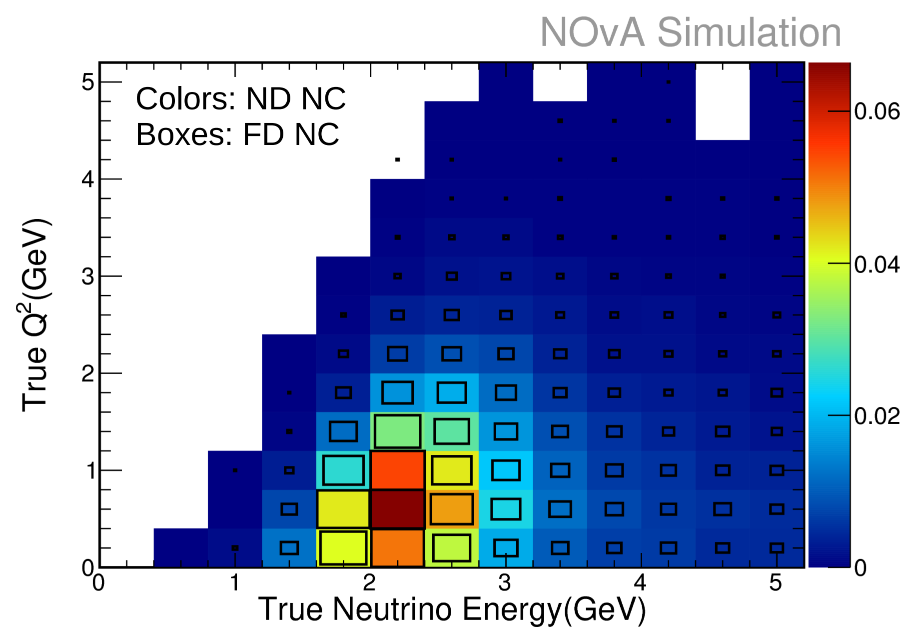


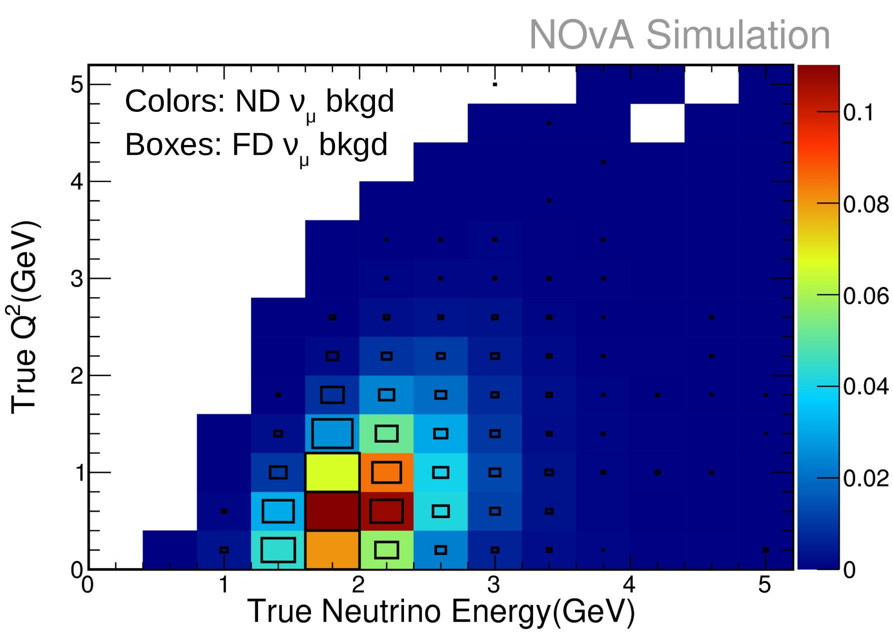


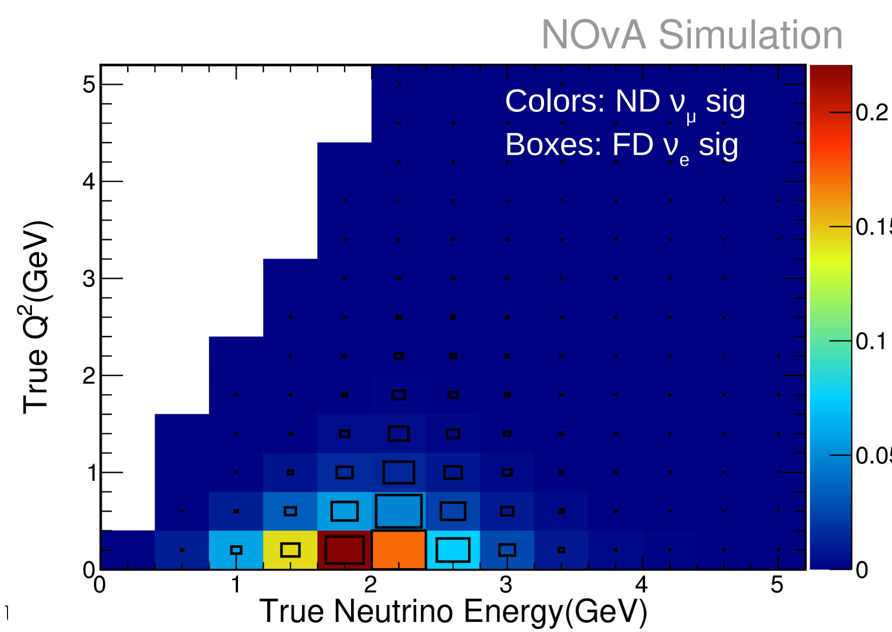


ν_e appearance: ND/FD kinematic compatibility





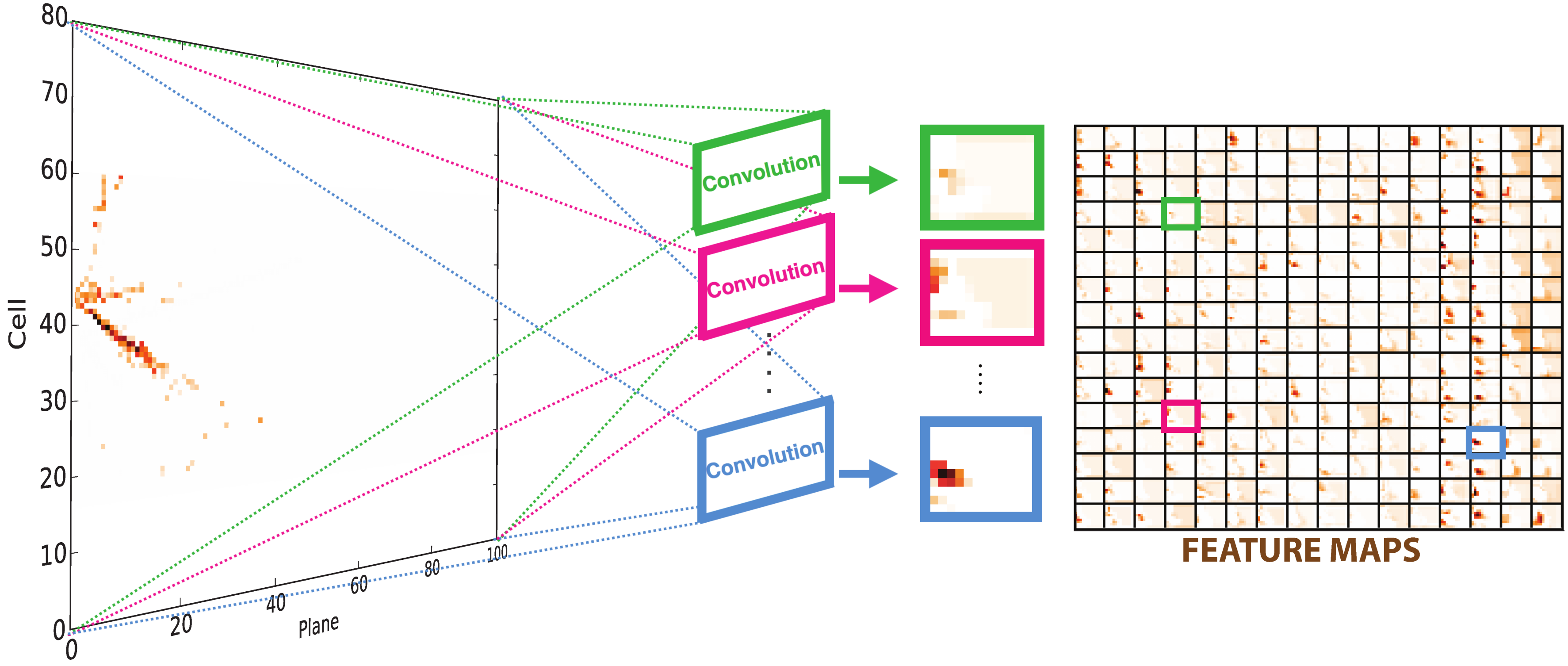




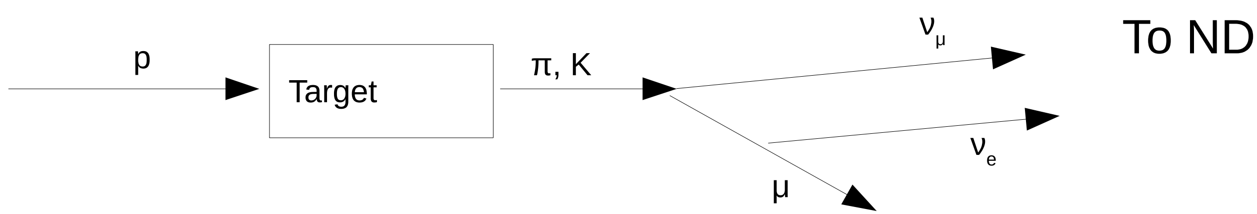
ν_e appearance: selection

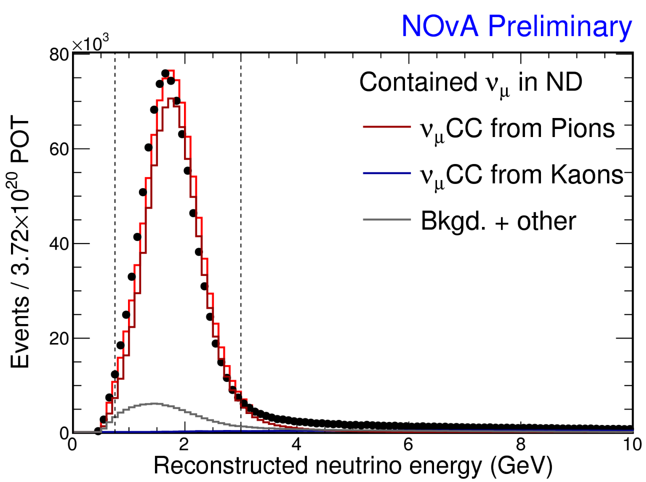
Event selection via a “Convolutional Neural Network”:

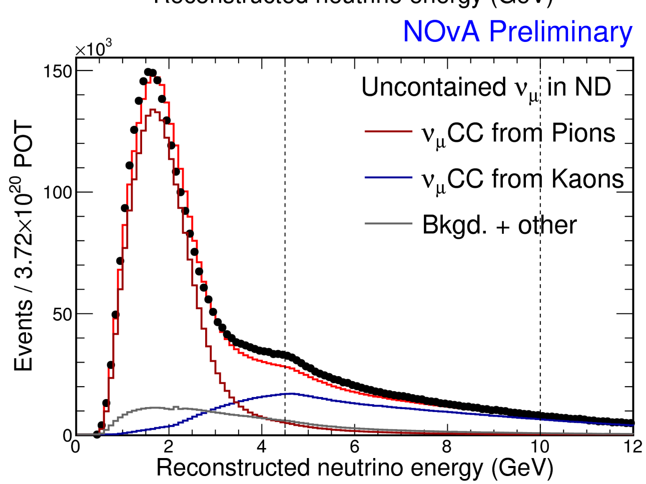
energy deposition patterns treated as images, algorithm extracts representative abstract features by applying learned filters



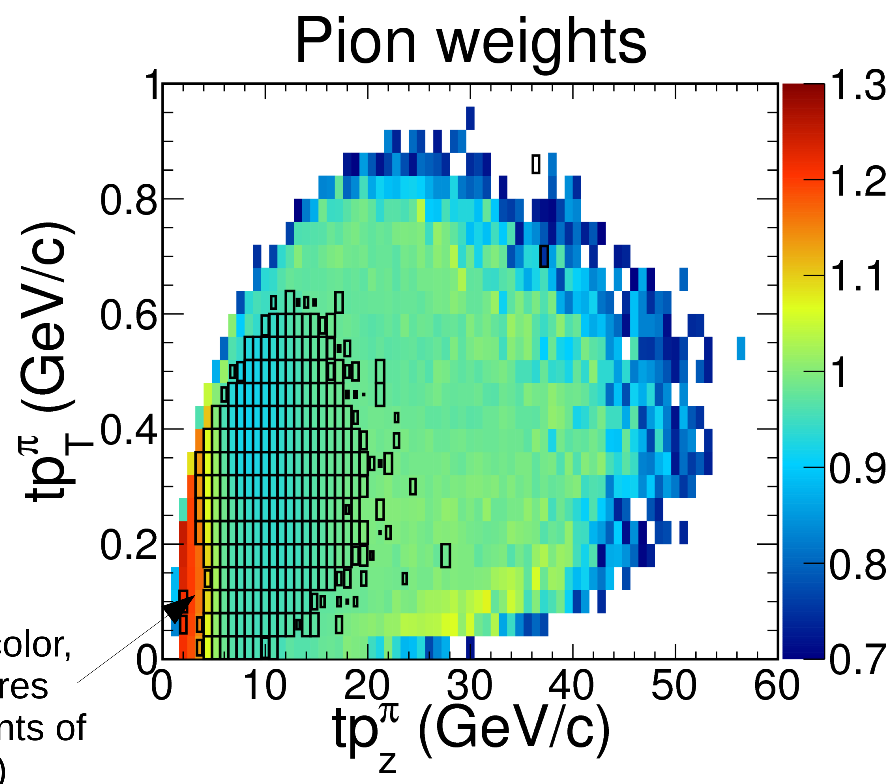
ν_e appearance: constraining beam ν_e bknd







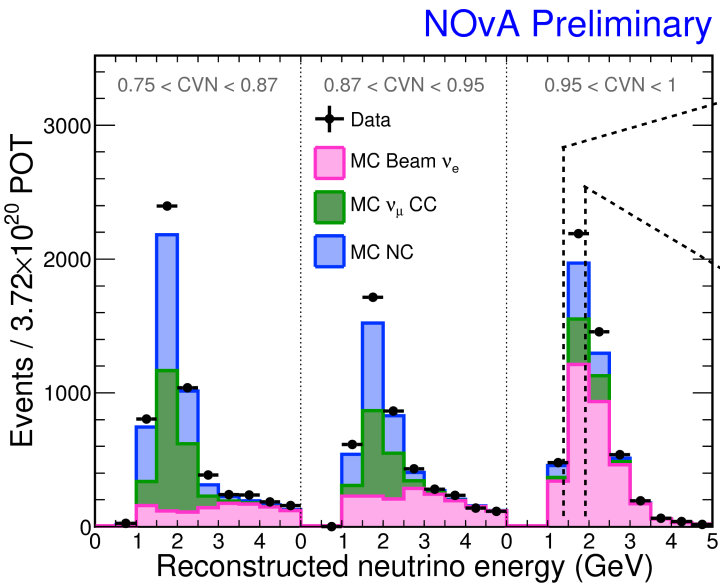
Assign discrepancies in ND ν_μ contained and uncontained samples to flux; **derive corrections according to parent mesons** (which also result in beam ν_e)

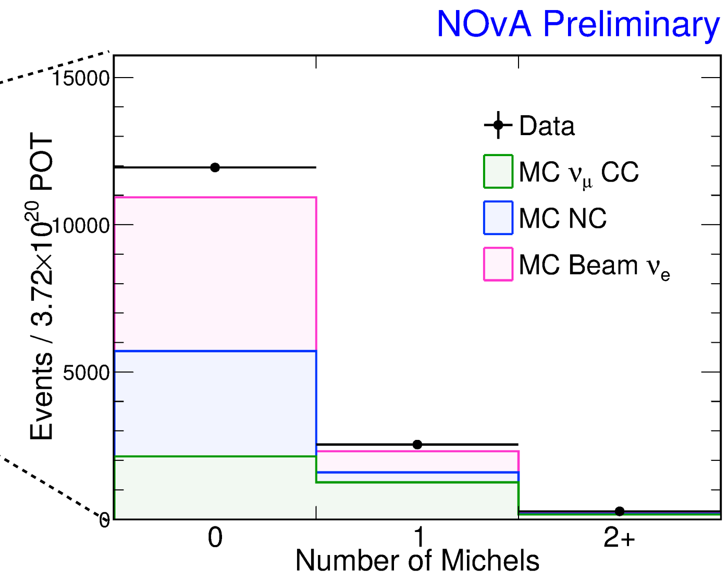


(weights in color, black squares indicate parents of beam ν_e)

Kaon-ancestor neutrinos get a single weight: 17%

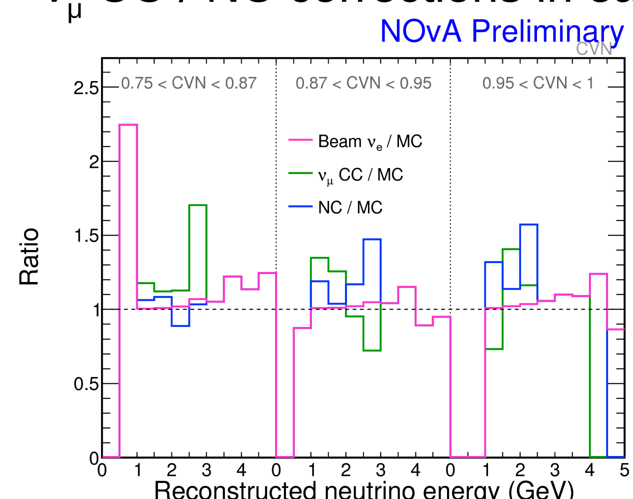
ν_e appearance: constraining ν_μ CC/NC ratio

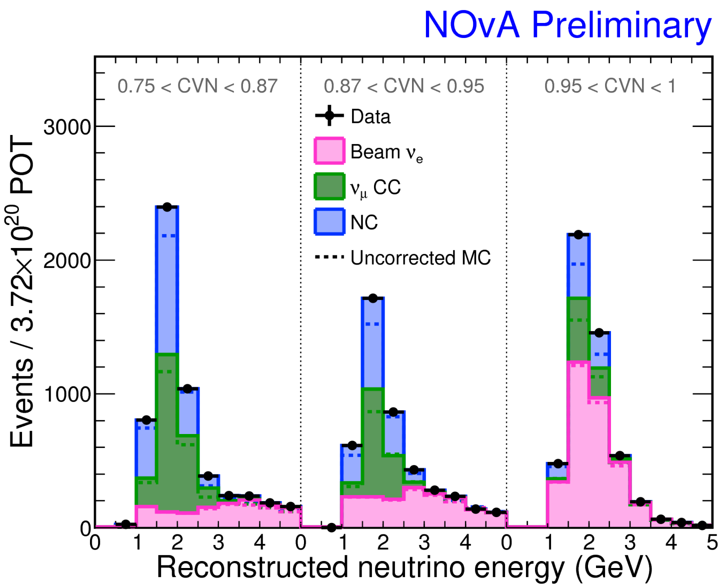




Examine distribution of Michel electrons in each bin of ND ν_e selected sample after beam ν_e constraint (prev slide)

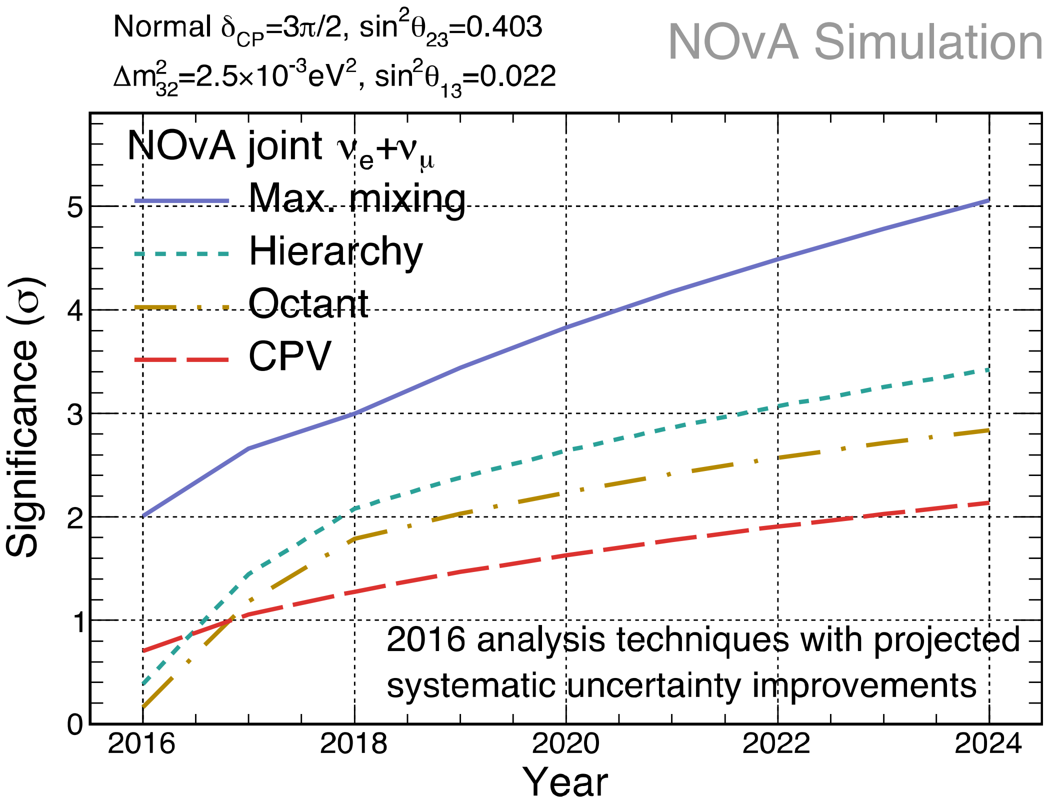
Fit these 30 distributions to determine ν_μ CC / NC corrections in each bin



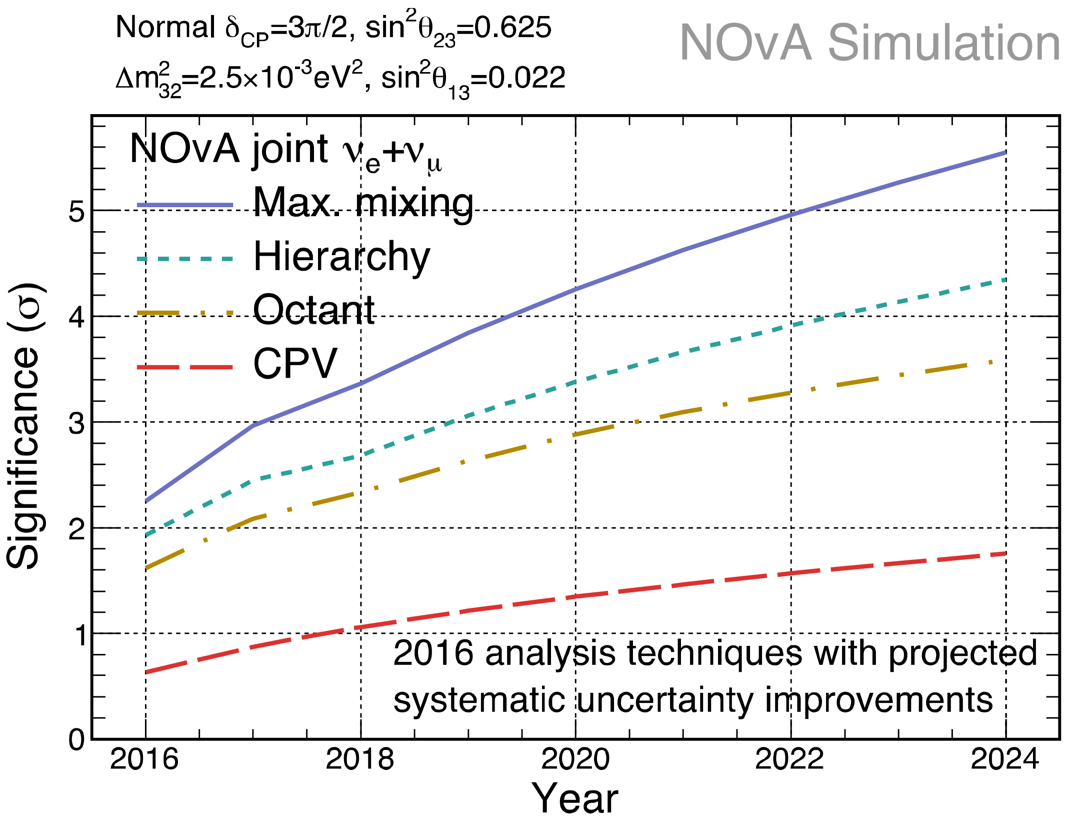


Future sensitivities

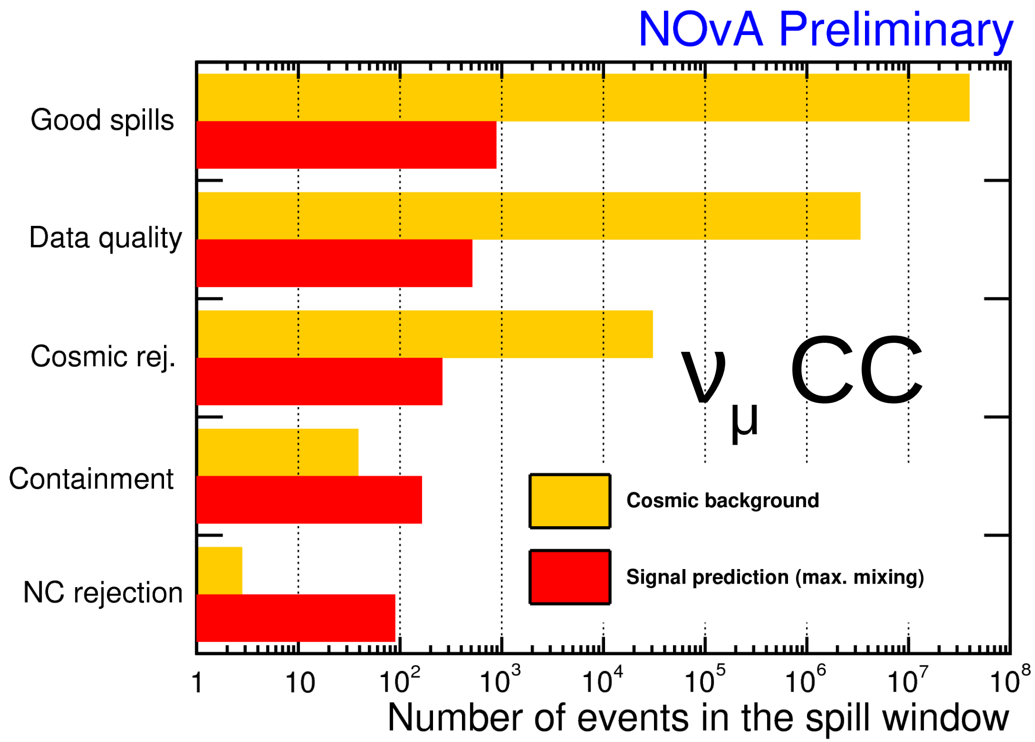
Lower Octant

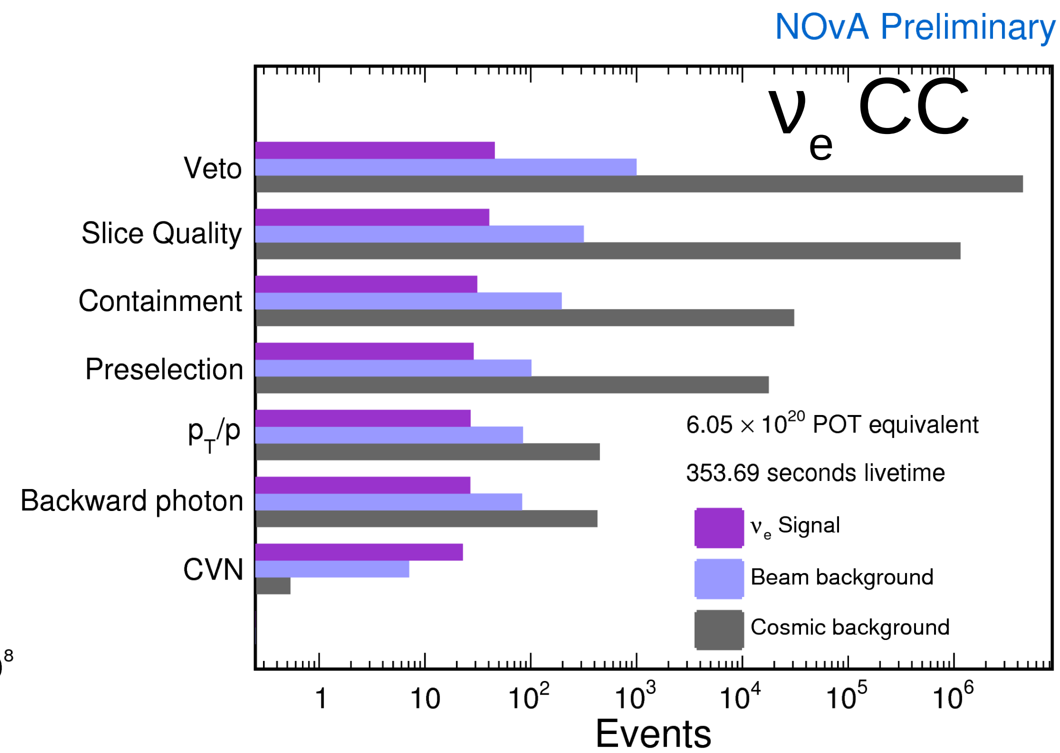


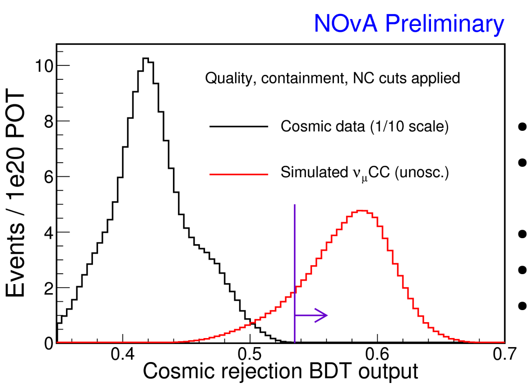
Upper Octant



Cosmic ray rejection





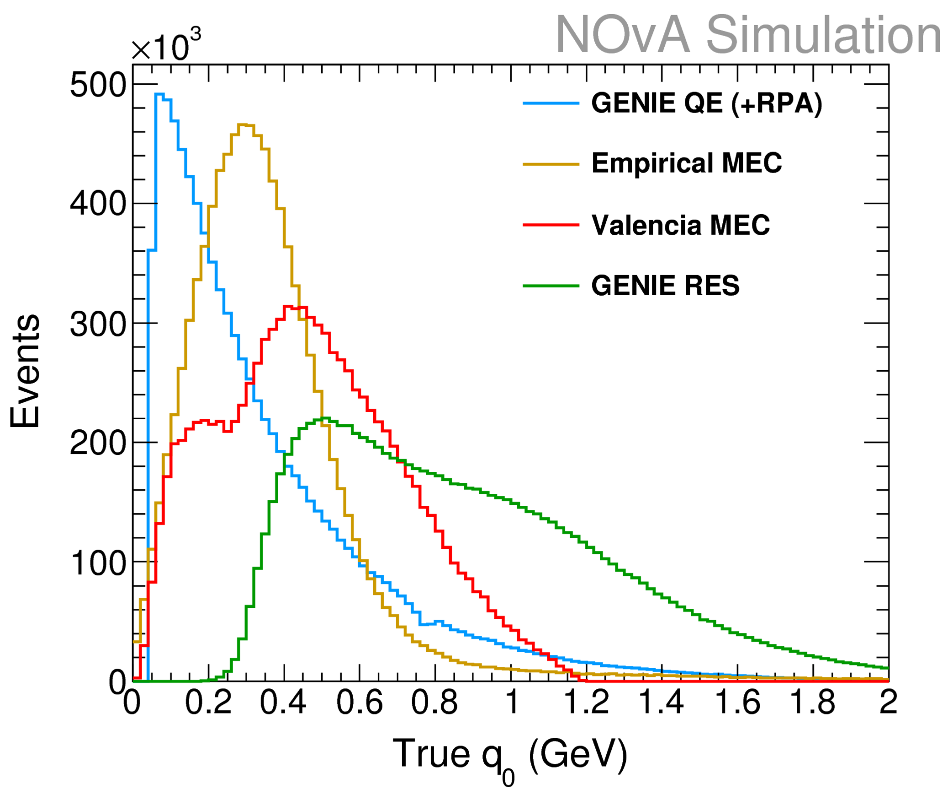


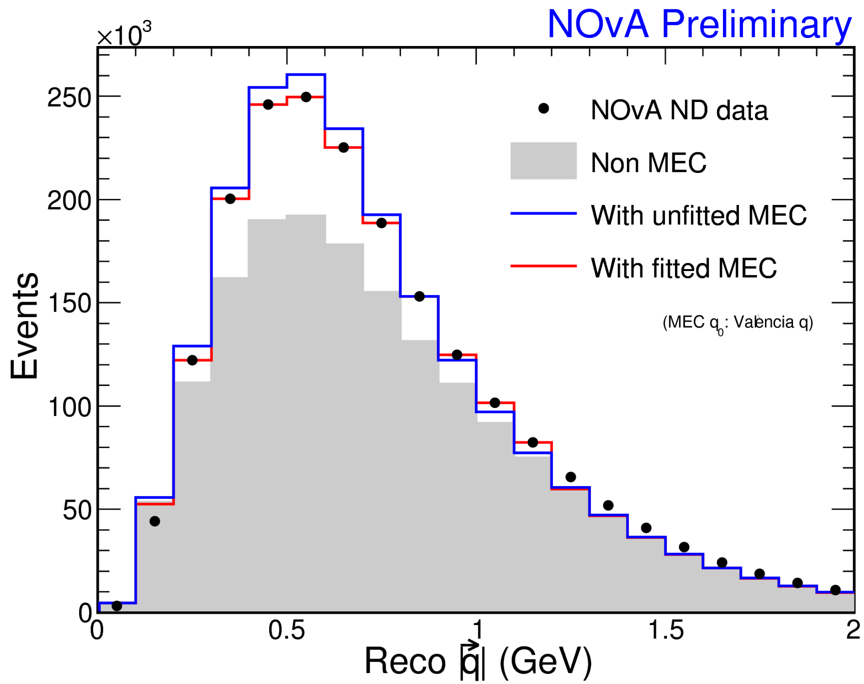
BDT:

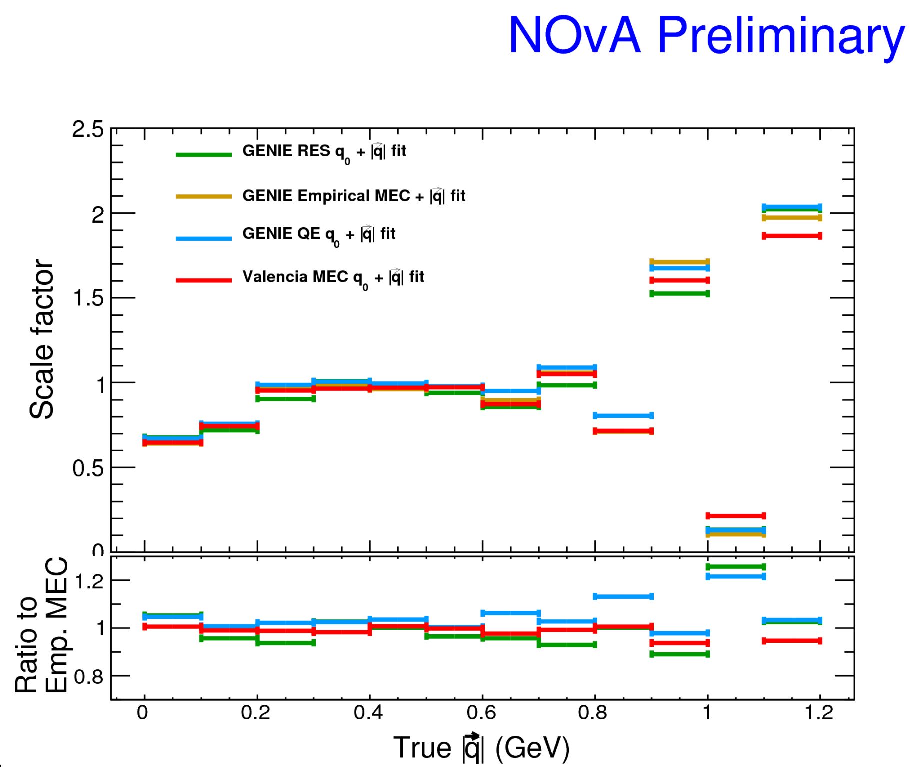
- Track direction
- Track start and end points
- Track length
- Energy
- Number of hits

Rejection power of about 10^7 (after 10^5 suppression from beam time-in) in both cases

Handling MEC



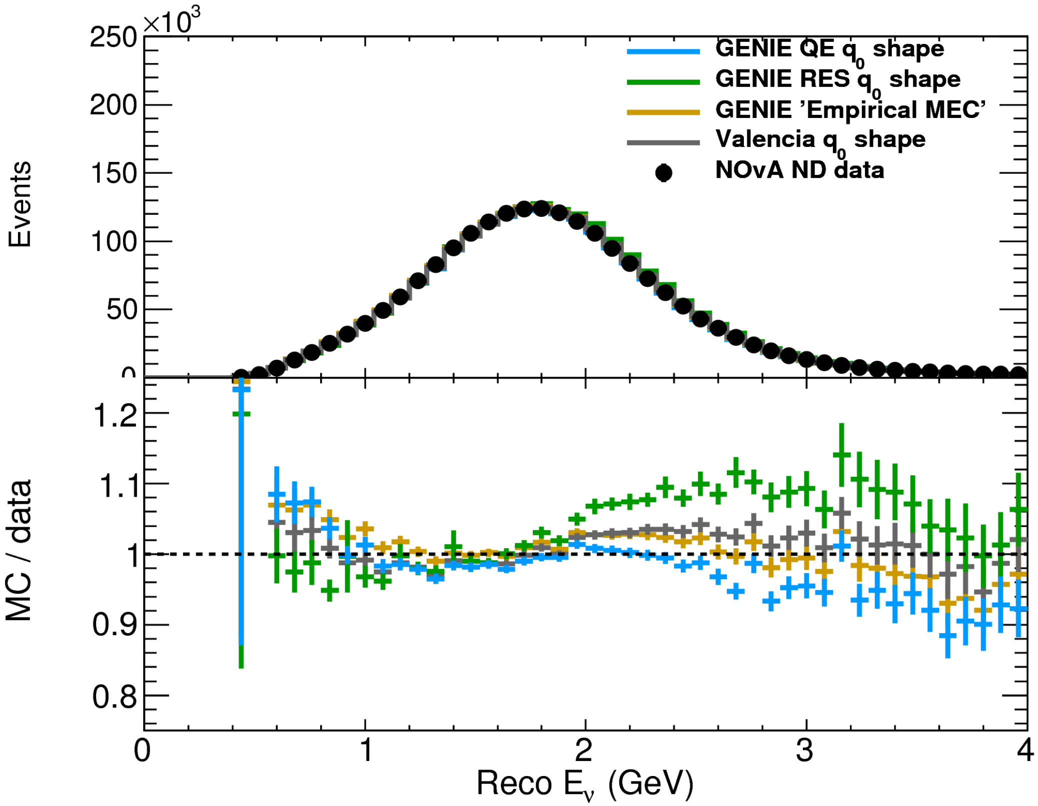




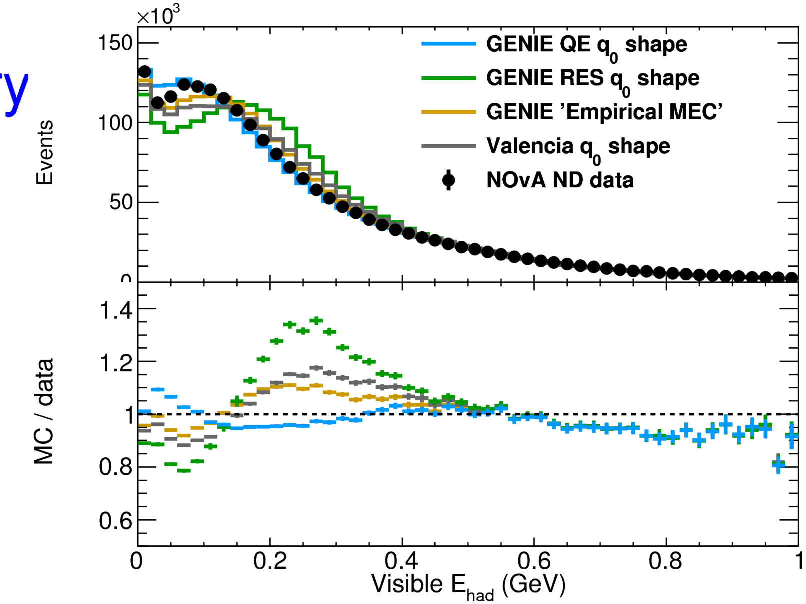
We make comparisons where
we use q_0 behavior of various models available to us
(by reweighting Empirical MEC)
and then fit true |**q**| shape (~normalization constraint)
to get best fit in reconstructed |**q**| against ND data

Handling MEC

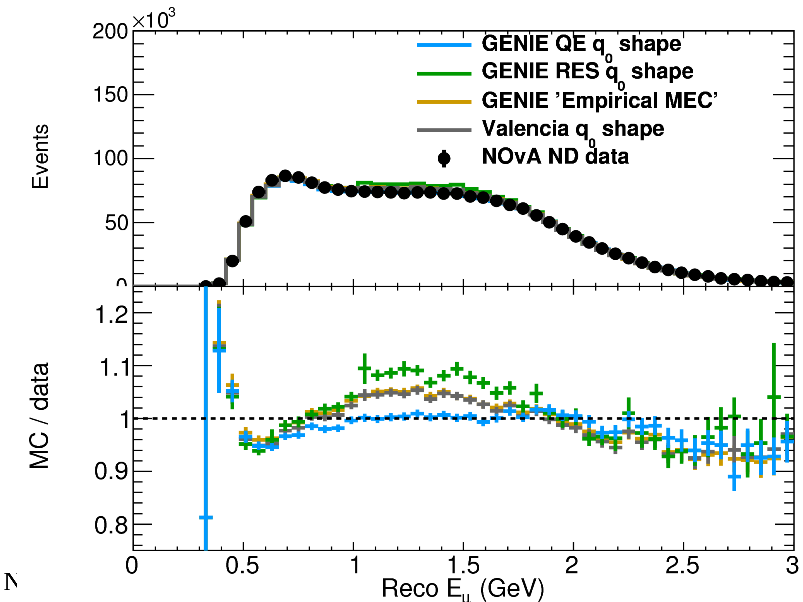
NOvA Preliminary



NOvA Preliminary

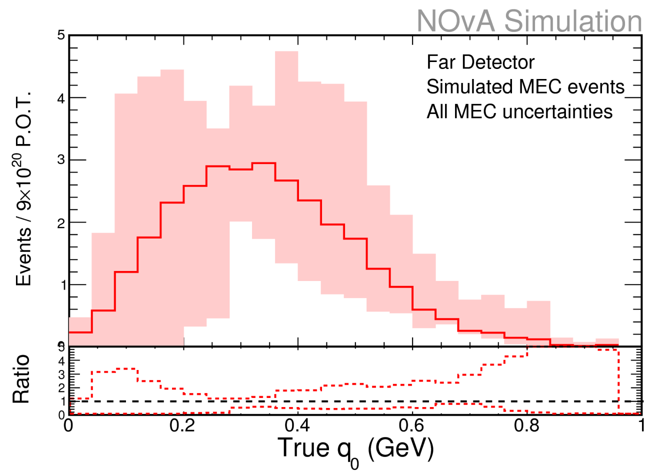


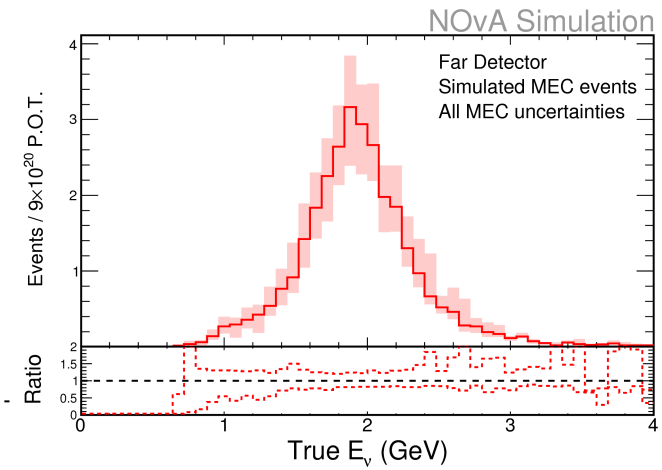
NOvA Preliminary



Effect of new MEC uncertainties (ν_μ disappearance)

Effect on just MEC prediction:





Effect on total prediction: