A tale of two experiments
NOvA & T2K

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Neutrino Generators Workshop, Fermilab (March 15 - 17, 2023)

On a joint adventure

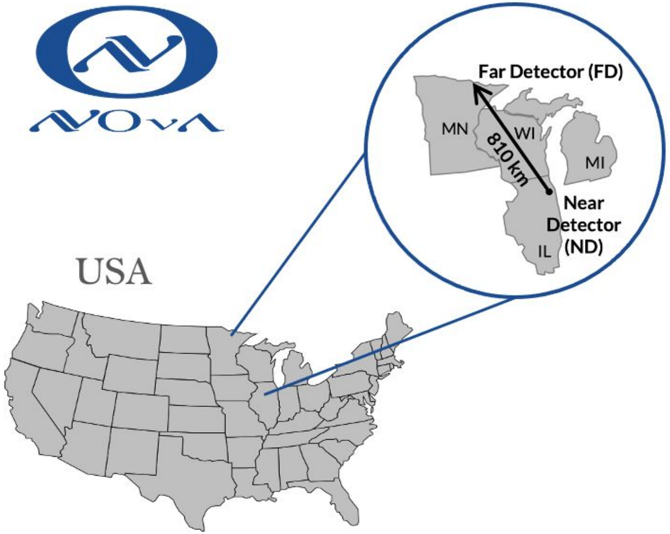
Comic Credit: Strange Planet

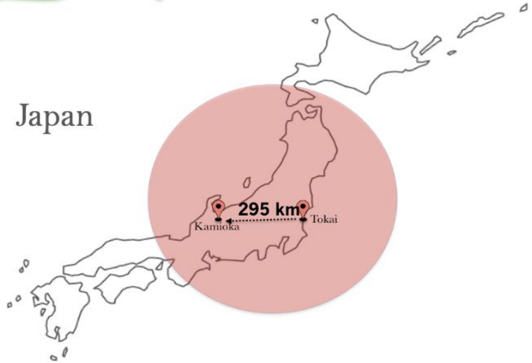
Setting Expectations:

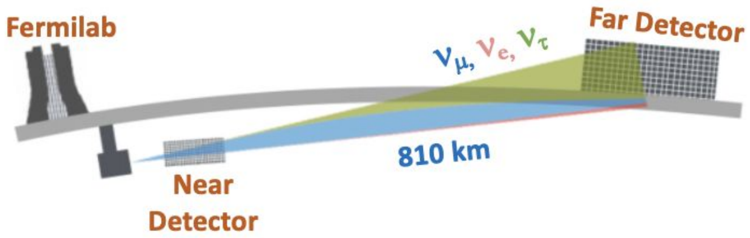
- Focus of this talk is on the NOvA-T2K joint analysis from a **tooling** point of view.
- The joint analysis is a big topic:
  - Many layers of interesting physics: *e.g.* detector response, cross-sections, oscillations, …
  - Many interesting analysis details: *e.g.* systematics, observable projections, statistical techniques, …
- The analysis is still in progress and not yet released (*coming soon*)
  - We will touch upon a few details in context for the main focus of this talk.
  - Reserve follow-up questions about the wider analysis details for later.

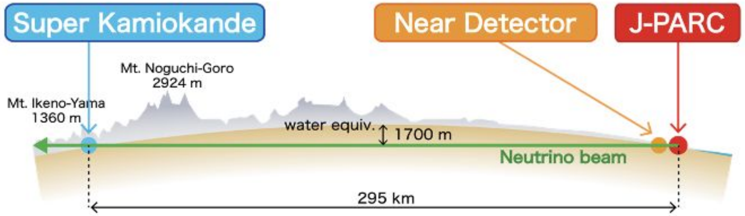
Overview

NOvA and T2K are long-baseline oscillation experiments that measure neutrino oscillations in accelerator-produced muon neutrino and antineutrino beams.



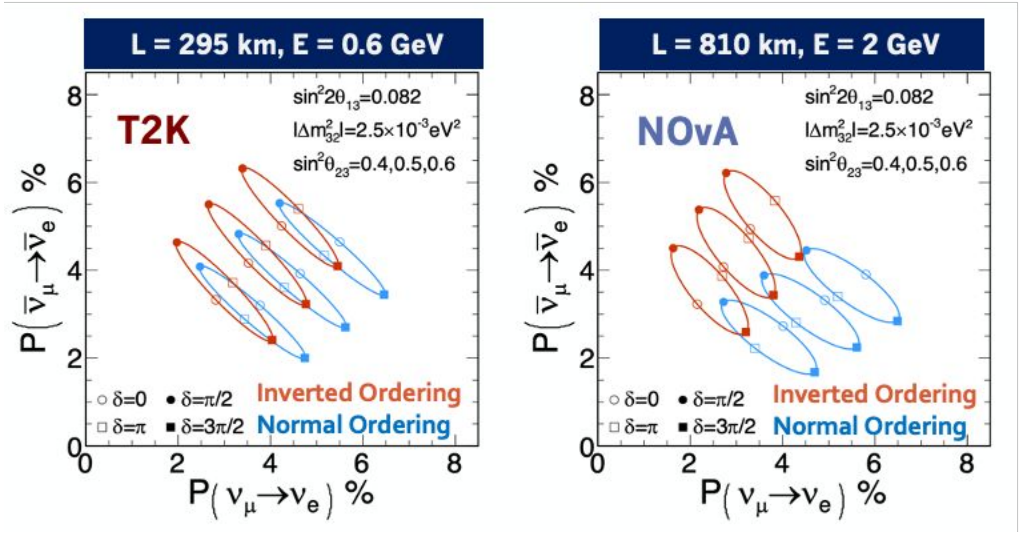






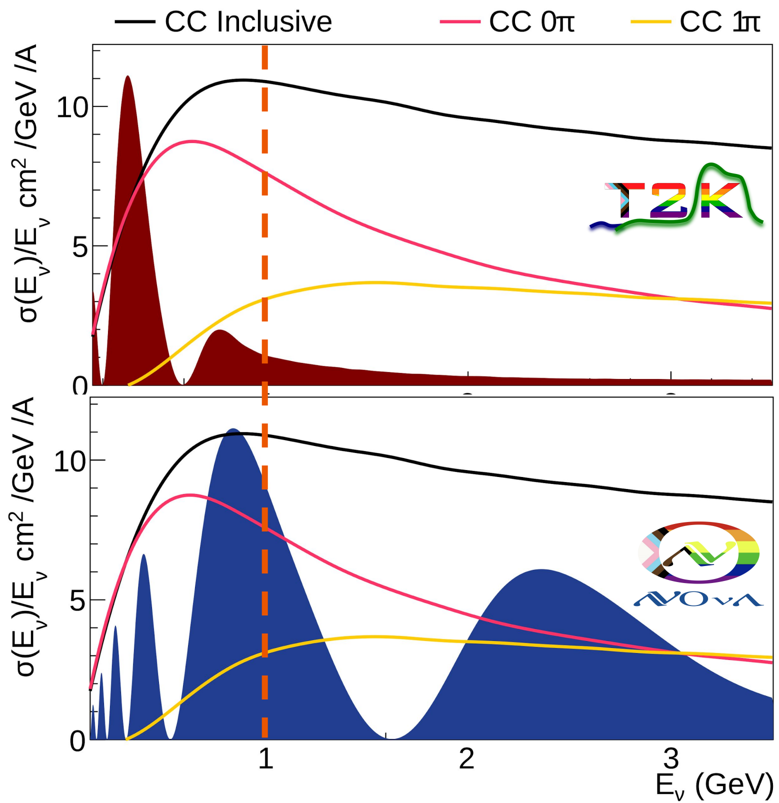
Joint Fit Motivation

- Important degeneracies broken in:
  - Mass-ordering & CPV
- More events!
- Different systematics:
  - Different neutrino energy regime so majority of sampled events come from different hard scatter channels
  - Different detector technology



Subtle nuclear effects

Hard-to-model hard scatter

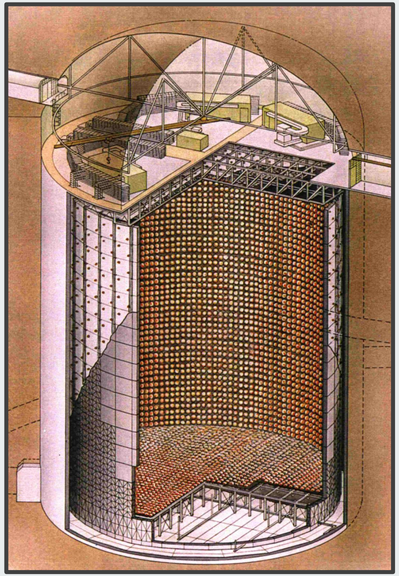


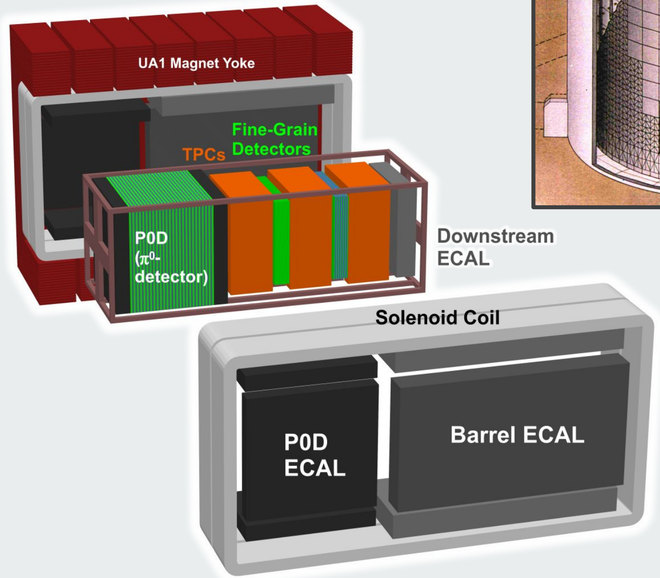
- Example surviving muon neutrino flux
- NEUT 5.3.3 predicted topological cross-sections

Detector design, fit strategy & interaction models

T2K detectors

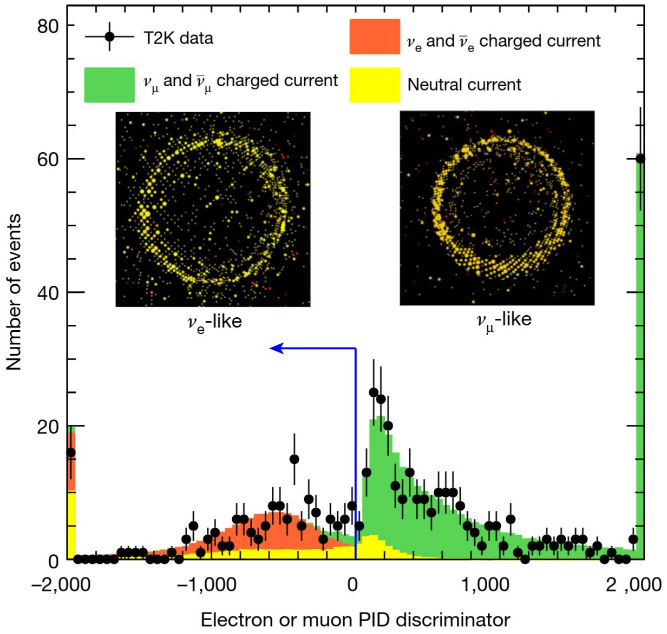
Far Detector, Super-K





Near Detector, ND280

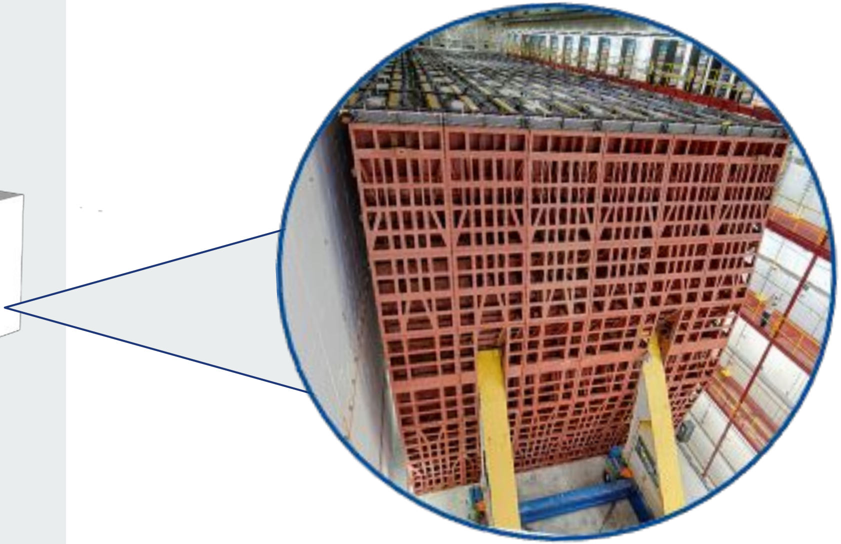
- Very different Near/Far detectors
- Both sensitive to final-state charged leptons and charged and neutral pions
- ND also sensitive to reasonably energetic protons



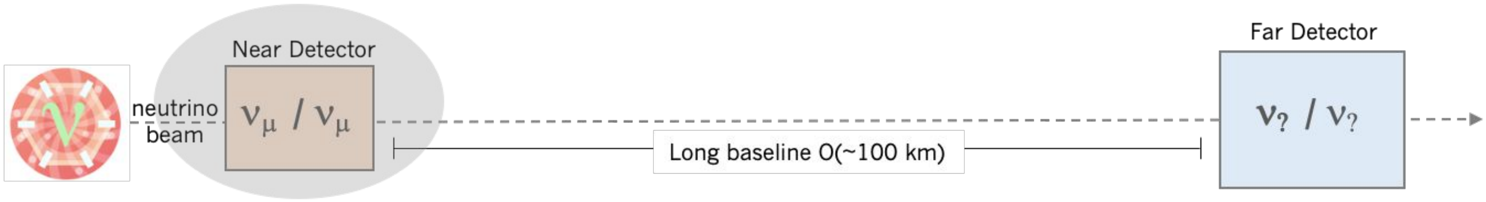
NOvA detectors

You are here

- Functionally identical near and far detectors that primarily differ in size.
- Segmented liquid scintillator detectors
- Particle detection via tracking and calorimetry.
- Optimized for electron showers:
  - 6 samples per X0 (~40 cm) and 60% active volume



Role of the ND



NEAR DETECTOR

Event rate, cross-section, oscillation probability

$$R(\vec{x}) = \phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_A \rightarrow \nu_B)$$

neutrino flux, detector response

FAR DETECTOR

➔ Near Detector provides significant data-driven constraints on:
- neutrino flux
- cross-section, and
- detector uncertainties

➔ The strategy to incorporate ND data constraint is determined by the detector design and varies significantly between the experiments.

T2K ND Strategy: ND data Fit

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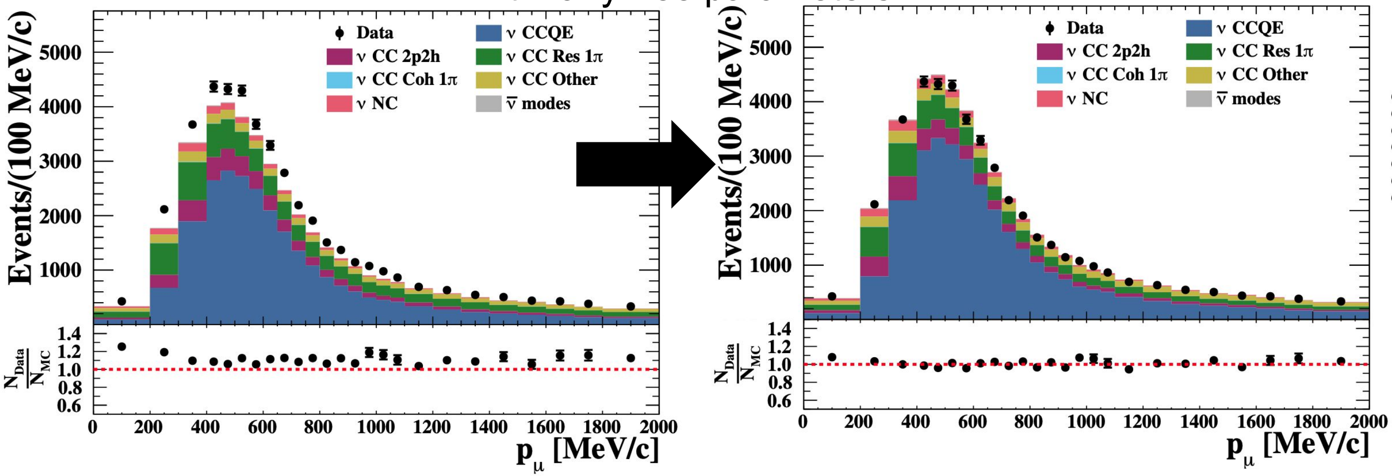
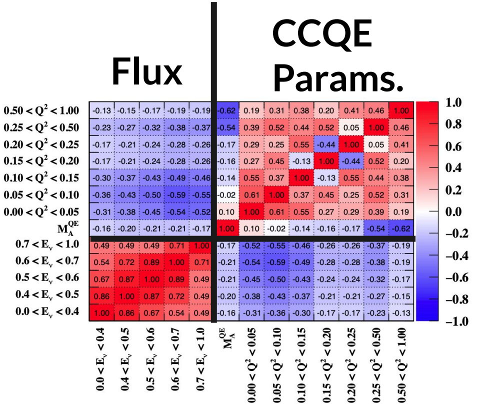
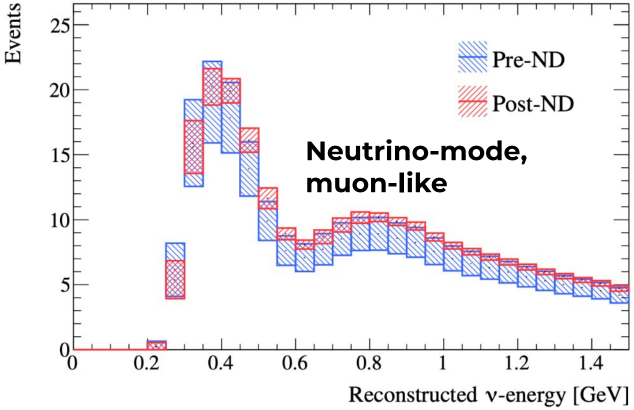
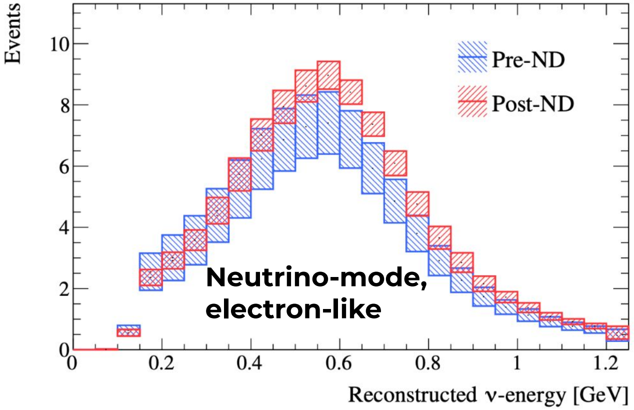
Fit many free parameters







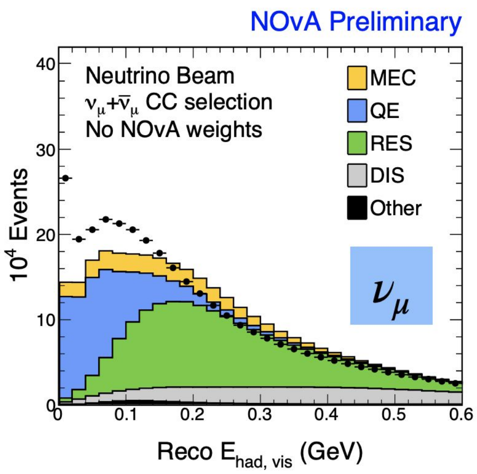


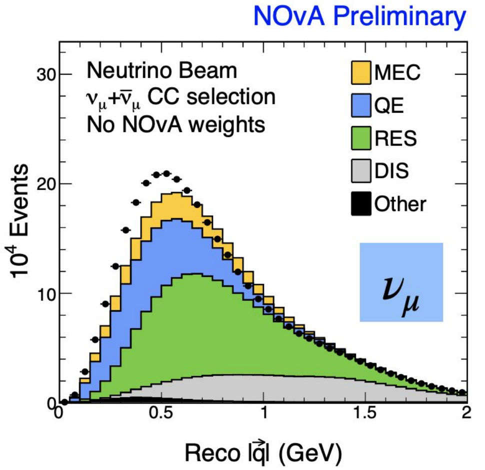
Far detector predicted event rates with oscillations

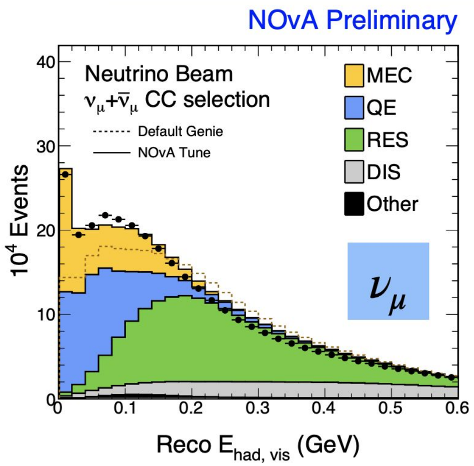
- Fit cross-section and flux models to ND data rate
  - 50-100 free cross-section parameters
- Use constrained and correlated flux and cross-section models to predict event rate at the FD for any oscillation hypothesis

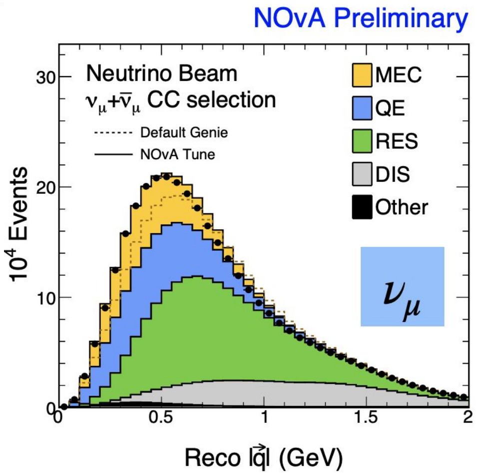
NOvA ND Strategy: Step 1 - Central Value Tune

- Nominal simulation is tuned in reco visible E_{had} and Reco $|\vec{q}|$ kinematic phase space.
- The simulation is primarily adjusted by tuning the MEC model to better describe NOvA ND data.
- The purpose of the the tuning is to bring the model in vicinity of the ND data and cover remaining differences between the data and MC by appropriate systematics knobs.









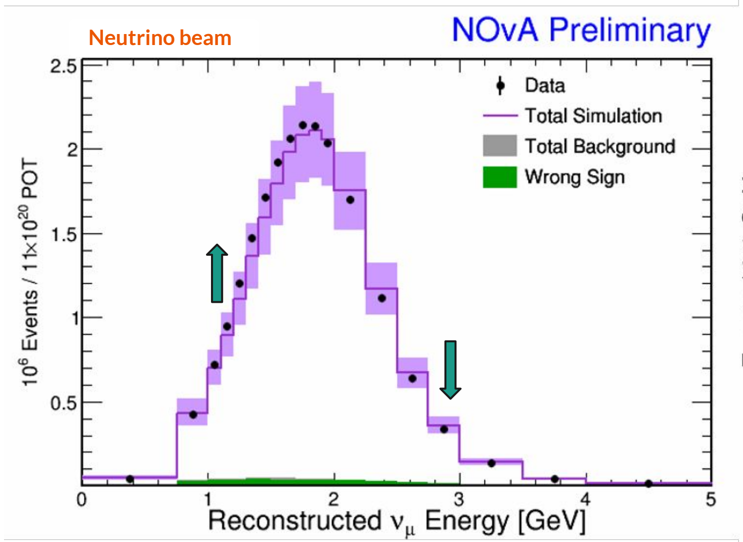
Full details in this NuFact'22 talk [K. Bays]

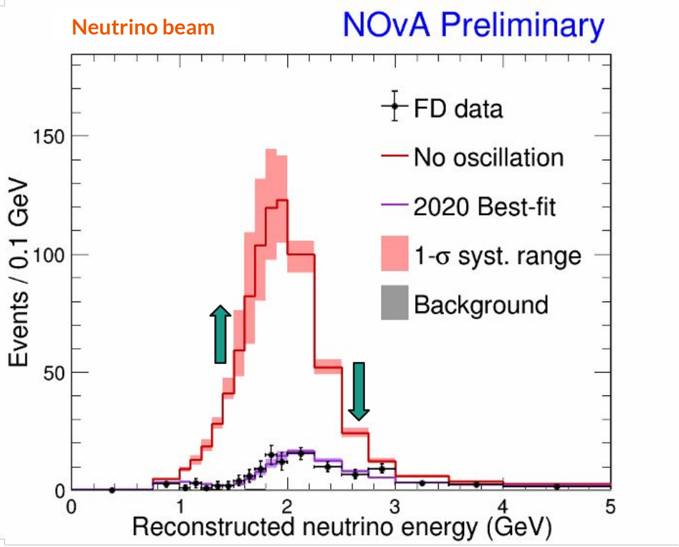
NOvA ND Strategy: Step 2 - Near-to-Far Extrapolation

- The ND data is then used to predict the no-oscillation spectra at the FD using simulations and related systematic uncertainties to model differences between the two detectors in flux, acceptance and cross-sections.

- CC inclusive ν_μ data from the ND is used to predict ν_μ and oscillated ν_e signal spectra at the FD.

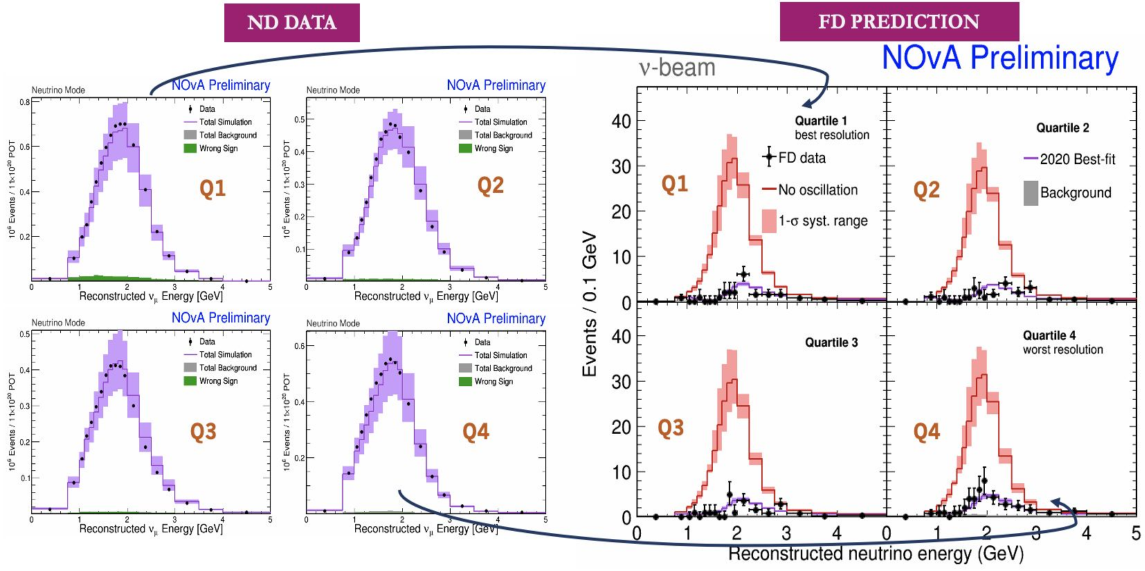
- Beam ν_e events from the ND are used to predict ν_e backgrounds at the FD.



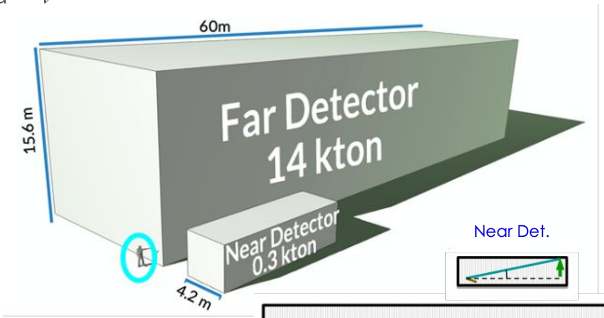


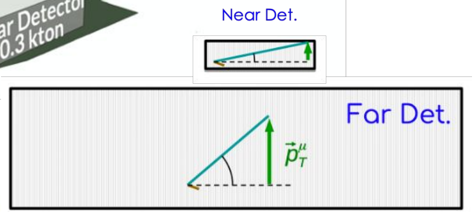
NOvA ND Strategy: Step 2 - Near-to-Far Extrapolation

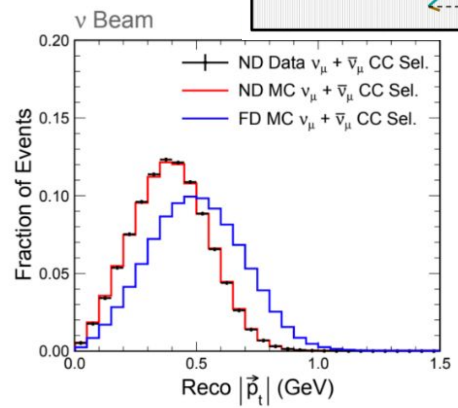
- To enhance the accuracy of the predictions : ND and FD events are kinematically matched by dividing the samples into 4 bins of hadronic energy fraction (E_{had}/E_{ν}) and 3 bins of transverse outgoing lepton momentum (p_T^{lep}) for a total of 12 bins.



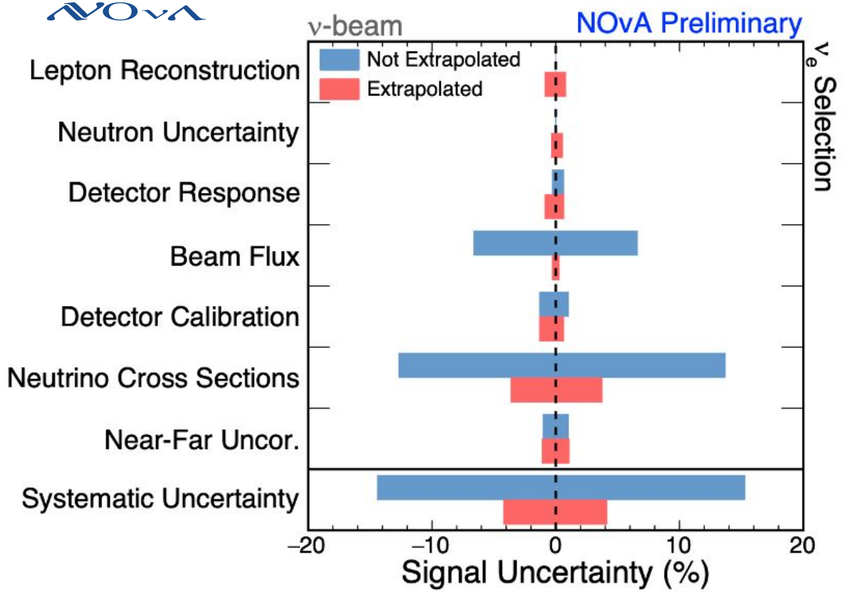
4 Quartiles of hadronic energy fraction. Further subdivided into 3 bins of p_T^{lep}







Different Strategies - Similar impact



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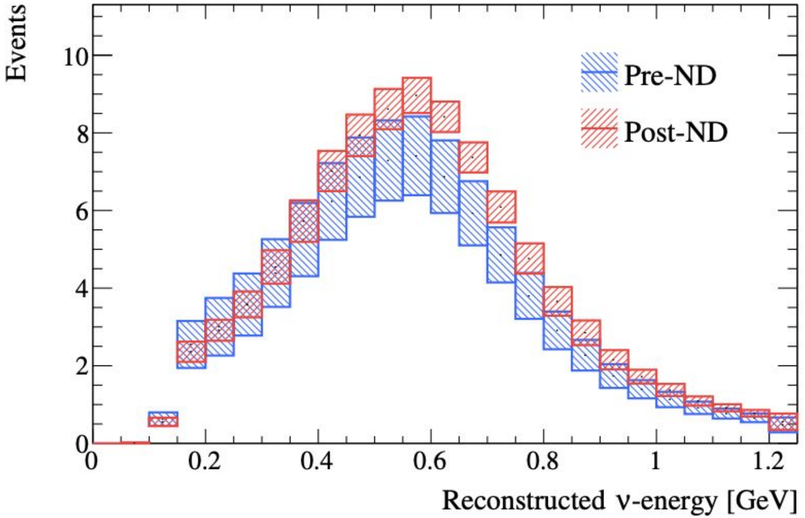


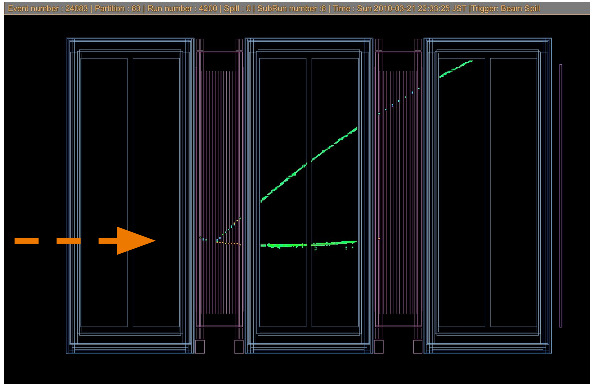
In both experiments, ND data constraints ~15% (prefit/not-extrapolated) systematic uncertainties on the FD ν_e sample to ~5% (post-fit/extrapolated).

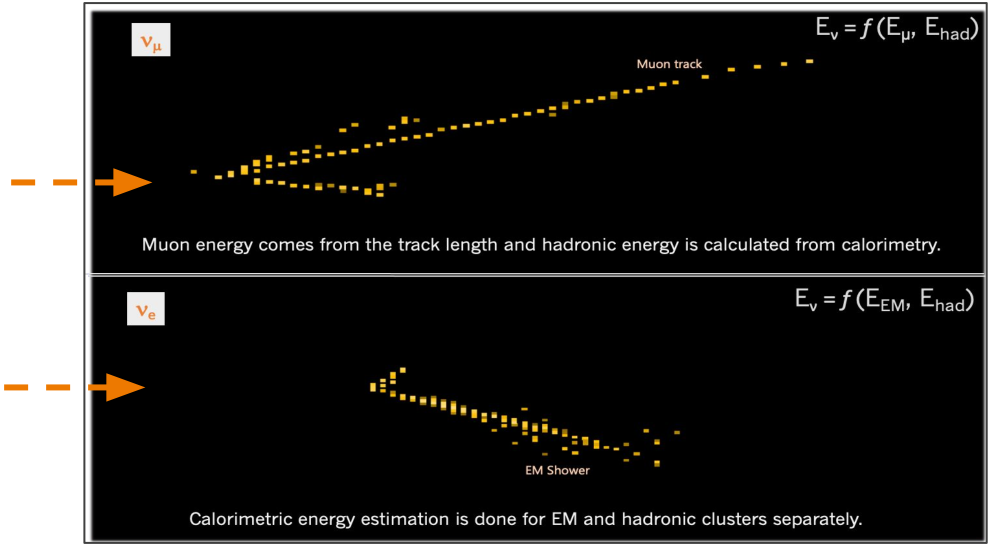
Reconstruction and choice of variables

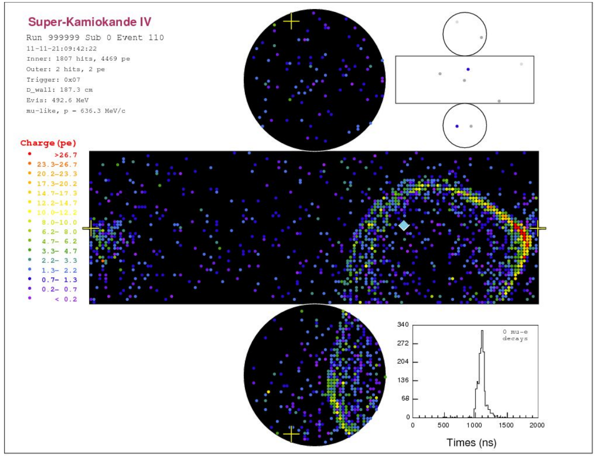
T2K: Incoming neutrino energy is reconstructed from the lepton kinematics (E_{RecQE}) and the samples are binned in muon kinematics (p, θ) and NPi

NOvA: Energy is estimated using track lengths for muon and calorimetry for hadronic and EM clusters. Binning in E_ν^{reco} and visible hadron energy fractions for muon samples and E_ν^{reco} and Particle-ID for electron samples.

These details affect which cross-section parameters are most important to constrain.







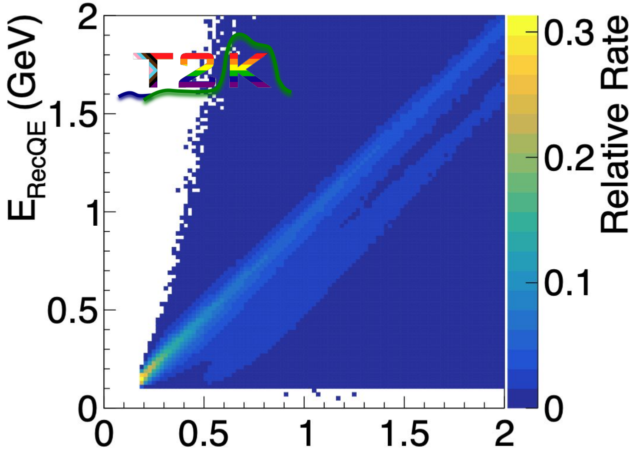
Role of generators, modeling and systematics

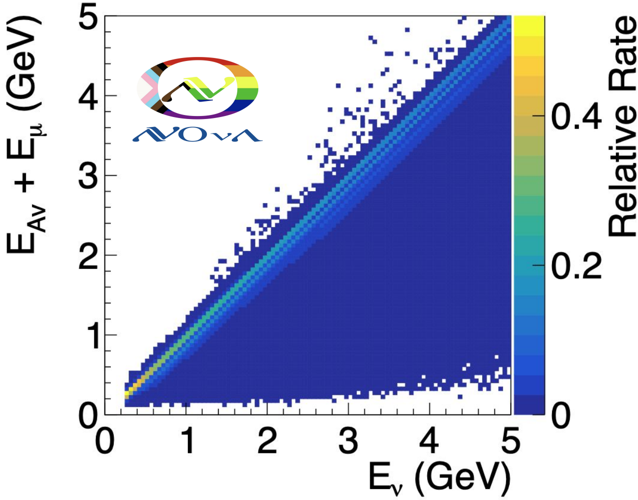
What The Generators Really Give Us

- Mapping between neutrino energy and observable kinematics:
  - Includes signal channel rate predictions
- Background rate prediction
- Connections between neutrino energies:
  - Near and far detectors see different energy spectra
  - T2K and NOvA see very different energy spectra

- Oscillation analyses depend on generators to predict energy smearing to know where to 'put' the oscillation effects in observable spectra

- Practically built from composite models with many moving parts:
  - Initial state and final state effects
  - Multiple hard scattering channels
  - Neutrino flavor effects
  - Each part is uncertain





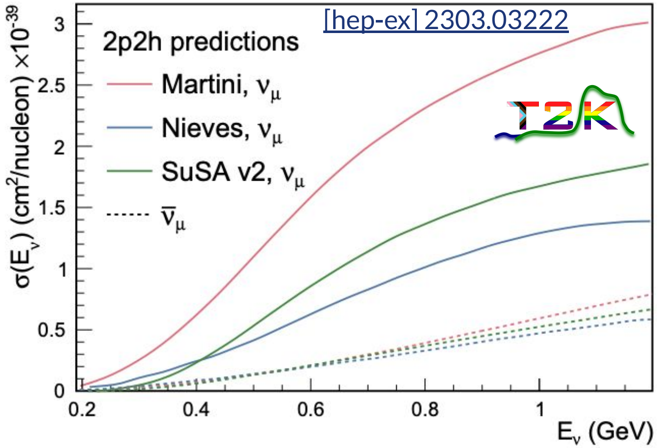
Interaction models

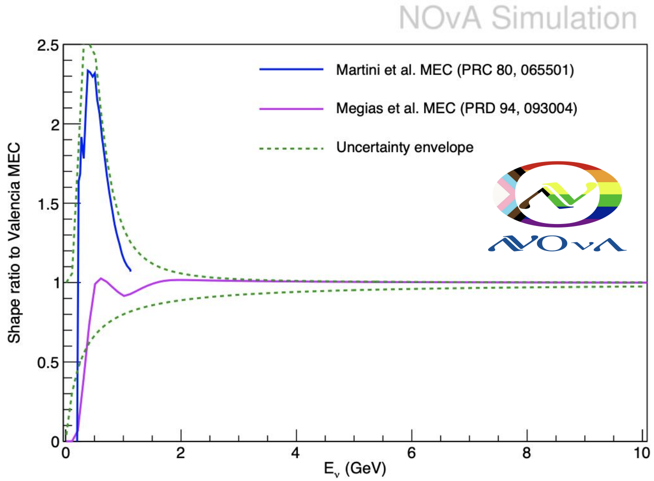
- Models and systematics used for 2020 analysis [NOvA: PhysRevD.106.032004, T2K:arXiv:2303.03222v1] will be used in the joint fit.
- The base-models are tuned to internal (NOvA-ND data by NOvA) and external datasets.
- The tuning could modify the underlying models drastically (eg: NOvA's 2p2h tune.)

Experiment	Generator	QE	MEC/2p2h	RES	DIS	FSI
NOvA	GENIE v3.0.6	Valencia Local Fermi Gas Z-expansion axial form factor	Valencia* (*with NOvA 2020 tune)	Berger-Sehgal	Bodek-Yang	hN Semi Classical Cascade (*fit to pion scattering data)
T2K	NEUT 5.4	Benhar Spectral Function M_A^{QE} form factor	Valencia	Rein-Sehgal	Bodek-Yang	Semi-Classical Cascade

Developing Cross-Section Systematics

- Systematics provide a uncertainty cloud around the (CV-tuned) composite interaction modeling.
- Cross-section systematics for the analysis have various origins, such as:
  - Theoretical uncertainties
  - Model-spread uncertainties





Ex: 2p2h energy dependence systematics from both experiments where nuisance parameters are added to cover the difference in energy dependence of different theoretical models.

Developing Cross-Section Systematics

- Systematics provide a uncertainty cloud around the (CV-tuned) composite interaction modeling.
- Cross-section systematics for the analysis has various origins, such as:
  - Theoretical uncertainties
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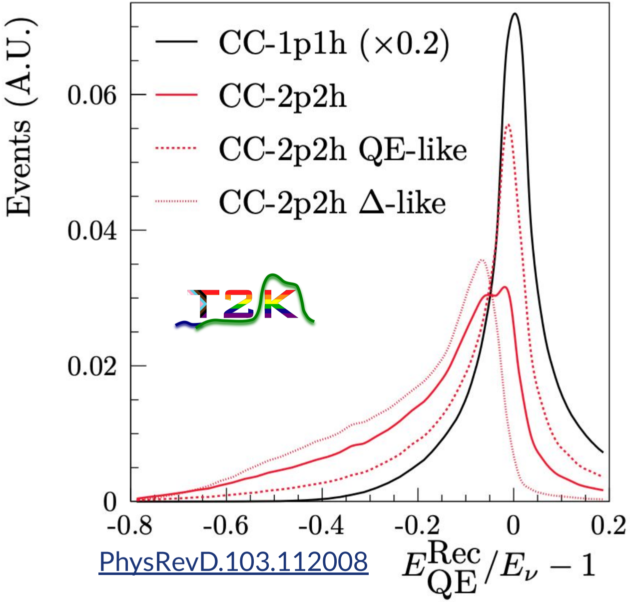
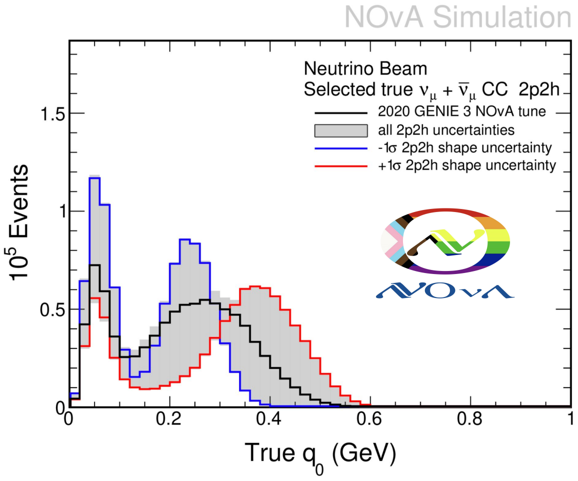
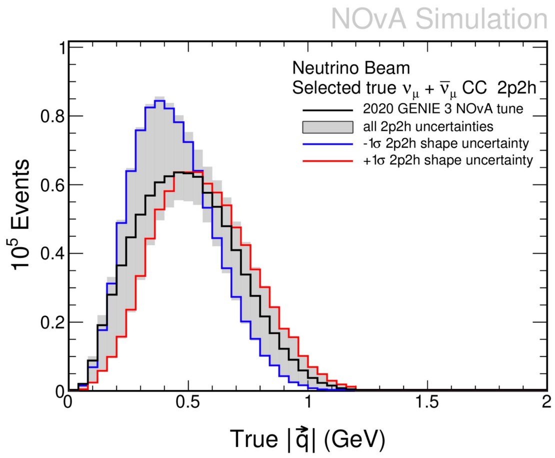
  - External or internal data
  - Additional effective parameters to include extra freedom of movement in certain kinematic phase spaces to provide appropriate coverage in the fit.



PhysRevD.103.112008





Ex: 2p2h shape systematics from both experiments where nuisance parameters are added to provide additional freedom for MEC to be more QE-like or RES-like.

Developing Cross-Section Systematics

- Systematics provide a uncertainty cloud around the central value rate prediction.
- Cross-section systematics for the analysis has various origins, such as:
  - Theoretical uncertainties
  - Model-spread uncertainties
  - External or internal data
  - Additional effective parameters to include extra freedom of movement in certain kinematic regions of phase space to provide appropriate coverage in the fit.

➔ **These *ad hoc* parameterizations are often intrinsically linked to the specific modeling, tuning and analysis choices.**

➔ **The precise value of effective parameters aren't important as long as it correctly predicts the data and provides appropriate systematics coverage.**

Talking across experiments

Cross-Experiment Tooling

- Rely on public and internal tooling to connect interaction models between experiments
- NOvARwgt Eur. Phys. J. C **80**, 1119 (2020)
    - Status: Previous analysis version is public
    - Using 2020 analysis version for the joint analysis
    - Takes GENIE events and applies custom NOvA tune
- T2KReWeight
    - Never been public. Luke wants to change that, watch this space…
    - Takes NEUT events and applies custom T2K tune
- NUISANCE: P. Stowell et al 2017 JINST 12 P01016
    - Can parse proprietary generator event formats: NEUT, GENIE, others
    - Interfaces to weight engines (e.g. NOvARwgt and T2KReWeight) to expose a quasi-homogeneous framework for cross-generator and experiment MC truth studies and MC–data comparisons

Simulated Data Studies

Moving to a fully consistent model description and a set of systematics that work for both experiments' fit strategies and data is a complex task.

To begin, we investigate and bracket the scope for biases on the oscillation measurements by using *simulated data studies* that stress test different parts of the model tuning, systematics, and the fit.

Things to examine:

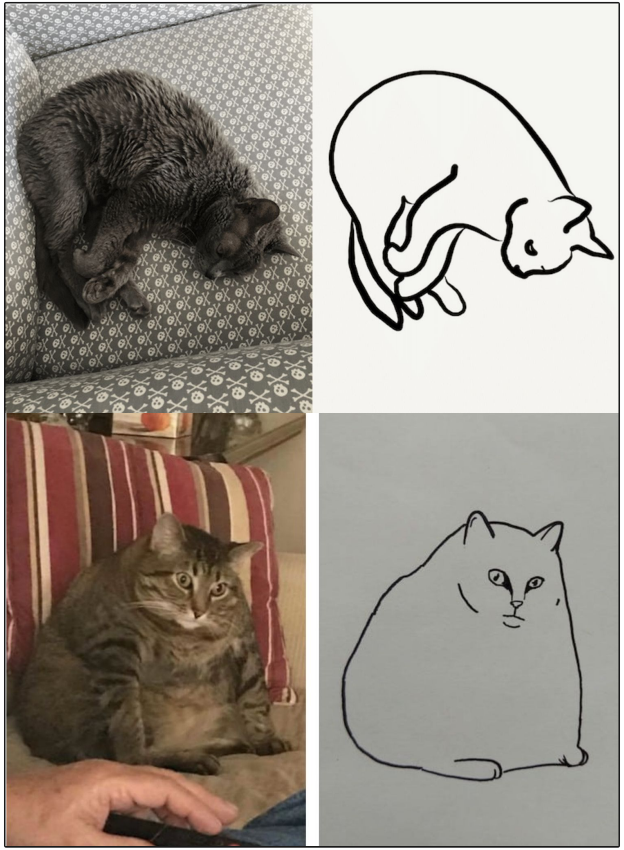
- Impact of using the T2K-like model and NOvA-like model on the joint fit
- Impact of changing key kinematic descriptions for a subset of the model
- Impact of correlating large systematics across experiments

Cateogry	NOvA Parameters	T2K Parameters
CCQE	ZNormCCQE ZExpAxialFFSyst2020_EV1 ZExpAxialFFSyst2020_EV2 ZExpAxialFFSyst2020_EV3 ZExpAxialFFSyst2020_EV4 RPAShapeenh2020 RPAShapesupp2020	M_A QE Q2_norm_0 Q2_norm_1 Q2_norm_2 Q2_norm_3 Q2_norm_4 Q2_norm_5 Q2_norm_6 Q2_norm_7 EB Dial C nu EB Dial C nubar EB Dial O nu EB Dial O nubar
MEC	MECEnuShape2020Nu MECEnuShape2020AntiNu MECShape2020Nu MECShape2020AntiNu MECInitStateNPFrac2020Nu MECInitStateNPFrac2020AntiNu	2p2h Norm nu 2p2h Norm nubar 2p2h C to O 2p2h Shape C 2p2h Shape O 2p2h Edep low Enu 2p2h Edep high Enu 2p2h Edep low Enubar 2p2h Edep high Enubar

Examples of systematic knobs used by two experiments for their QE and MEC models.

Reweighting Histograms in Truth Vars

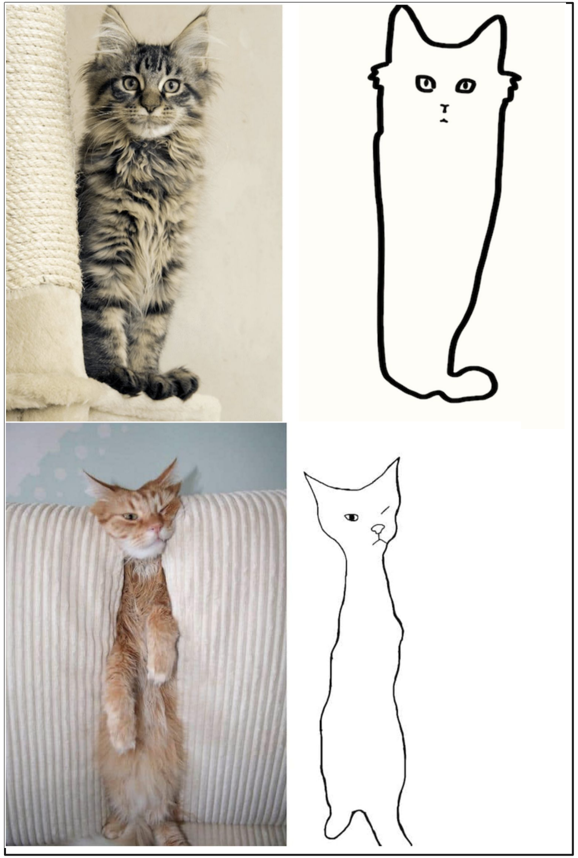
- To create simulated fake data from each experiments' nominal simulation, we create a weighting procedure to capture key normalization and shape differences between models.
    - Adopt a minimal approach that captures the *essential features* of the alternate model.



Credit: r/minimalcatart

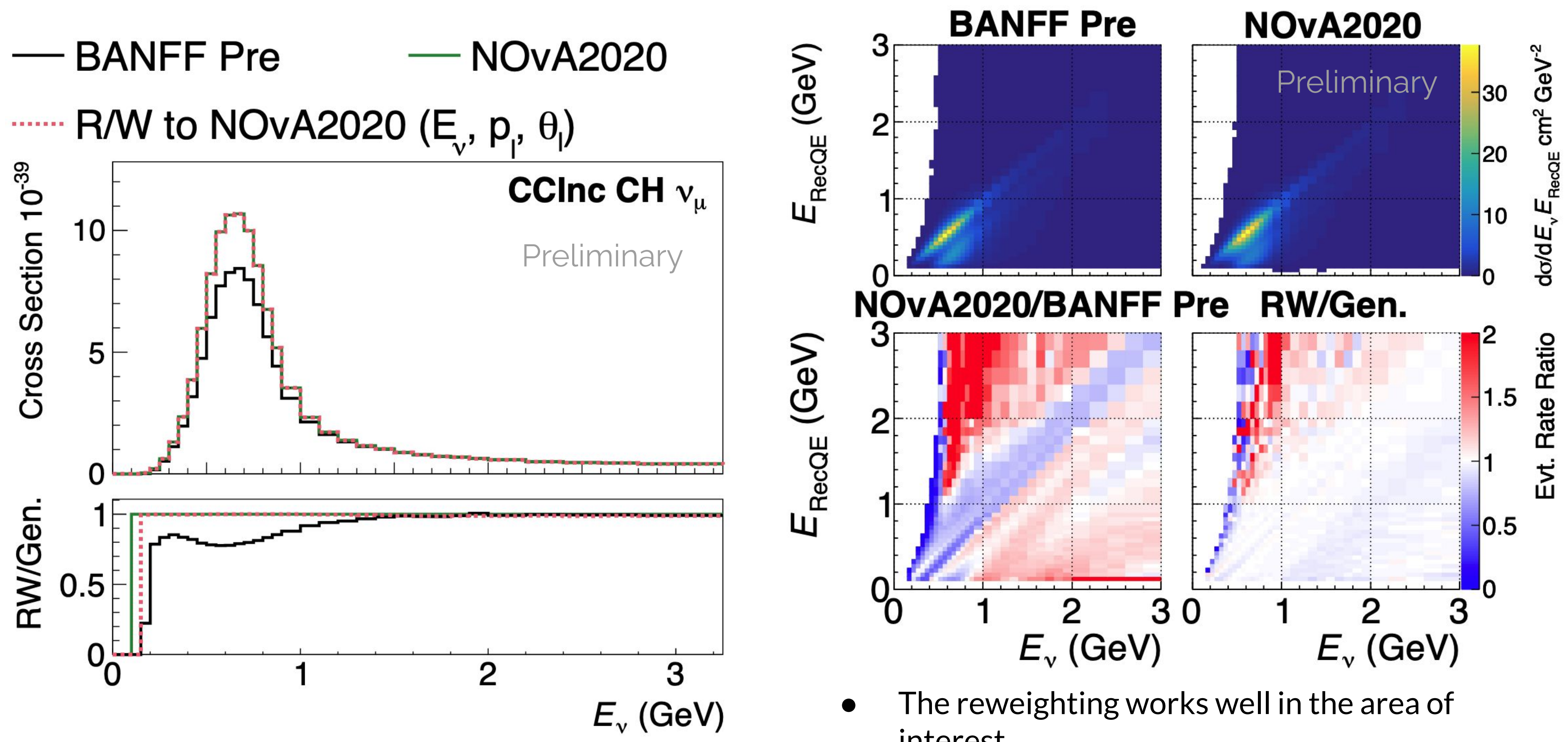
Reweighting Histograms in Truth Vars

- To create simulated fake data from each experiments' nominal simulation, we create a weighting procedure to capture key normalization and shape differences between models.
  - Adopt a minimal approach that captures the *essential features* of the alternate model.
- Things to consider:
  - Phase space overlap
    - Impossible to apply reweighting if there are no events in one of the distributions
  - Categorisation of events
    - True mode definitions do not map perfectly between generators
    - ⇉ Separate by NPi topology (0pi, 1pi, multi-pi, other) to individually capture their relative shapes and contributions.
  - Reweighting variables/number of dimensions
    - Reweighting in larger number of variables renders a better description.
    - Harder to manage > 3D histograms
    - Reweight in (E_ν, E_{had} and p_T) for NOvA and (E_ν, p_l, θ_l) for T2K.



Credit: r/minimalcatart

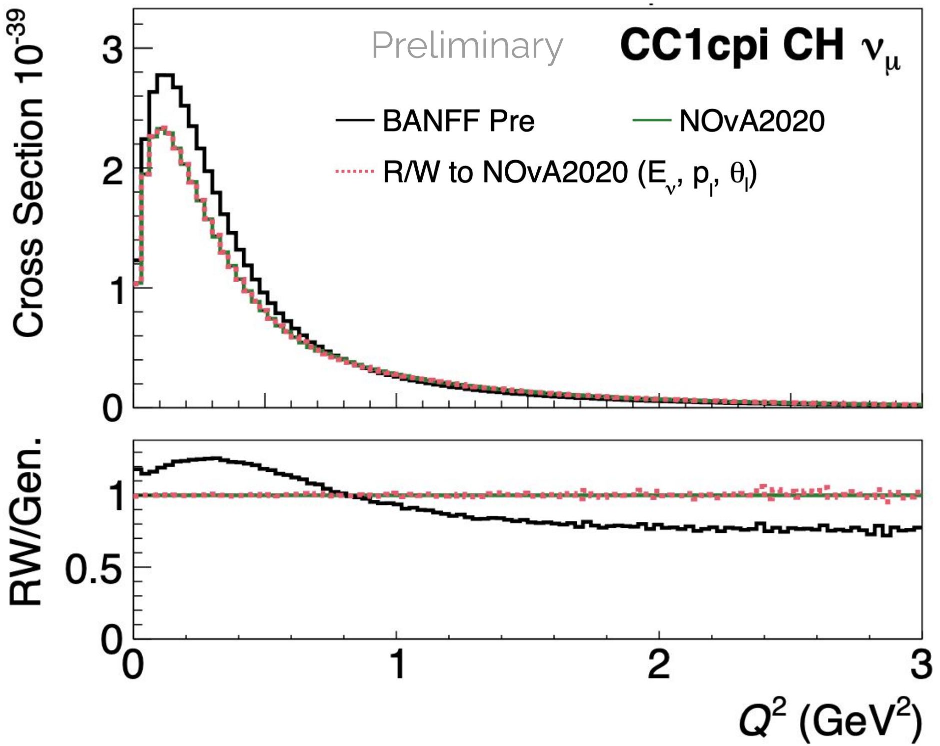
Validations of how well it performs

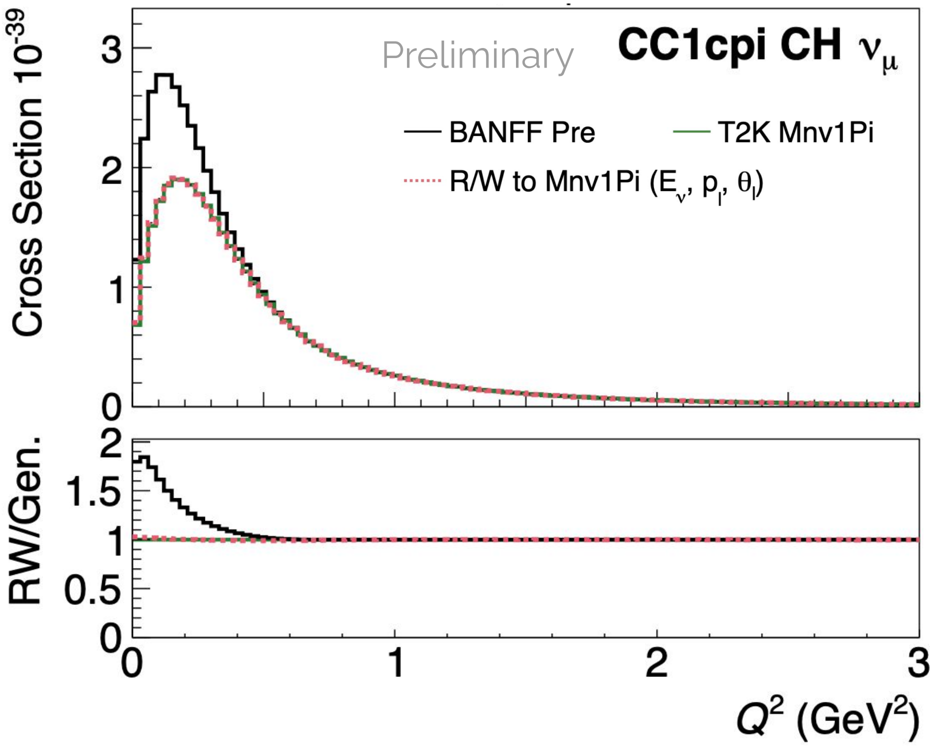


- The reweighting works well in the area of interest.

Reweighting applied to fake data

- Multiple variations of models (such as those detailed in arXiv:2303.03222) that modify the kinematic phase spaces very differently were mimic-ed using this reweighting approach successfully.





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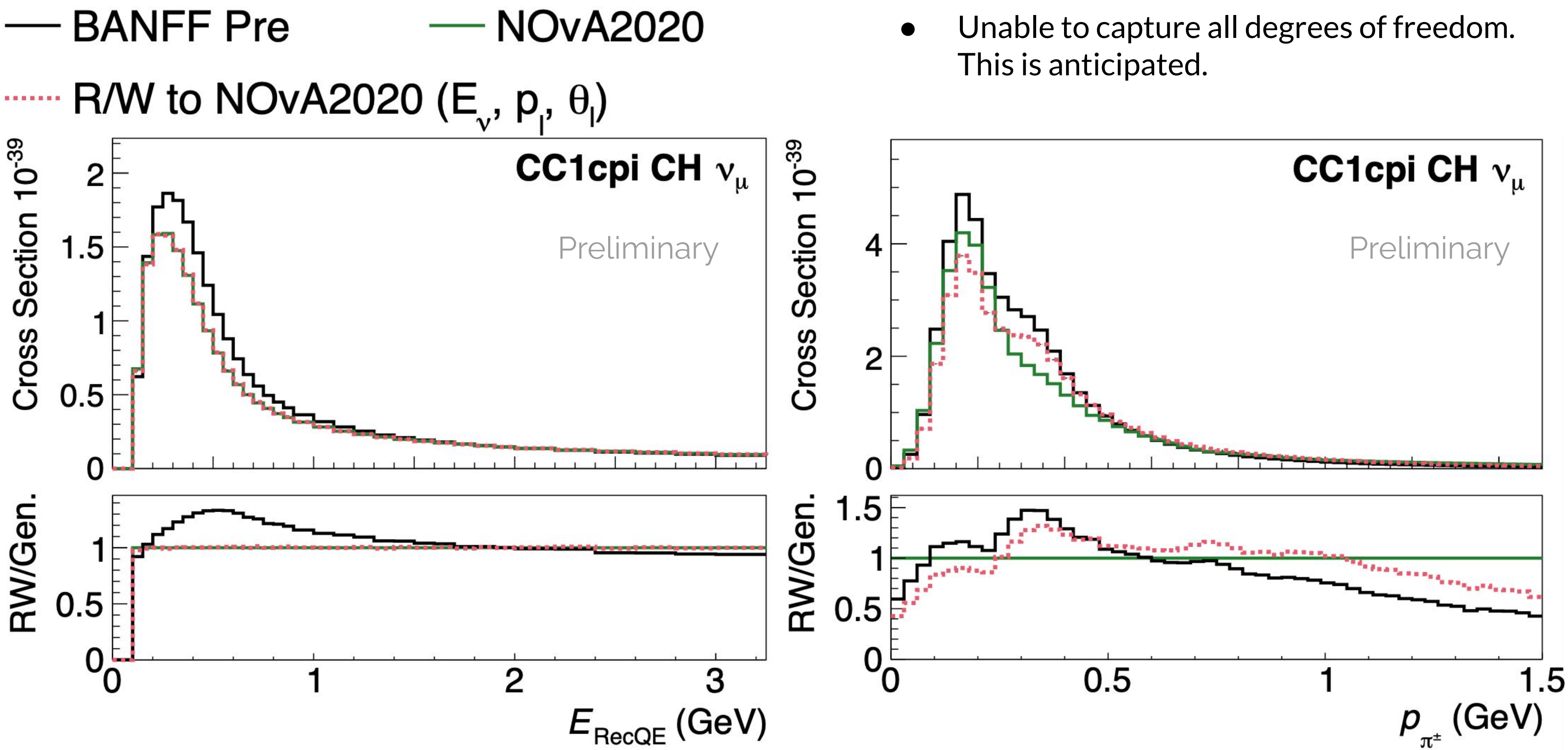
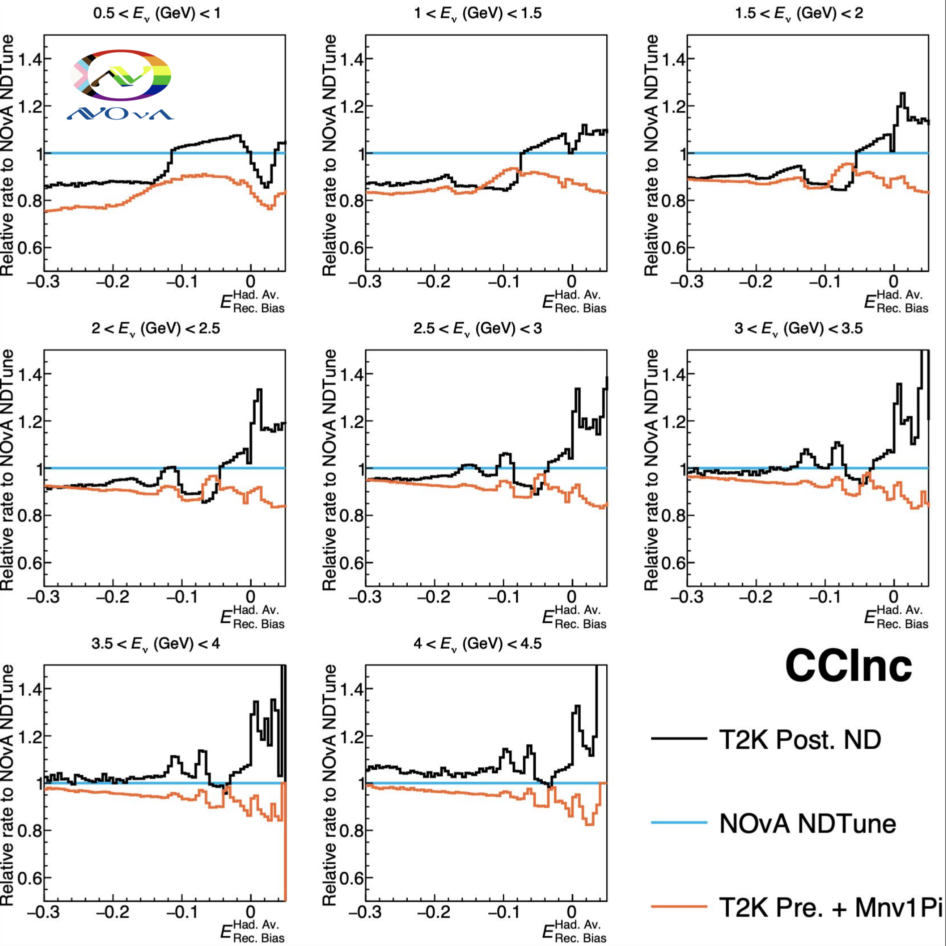
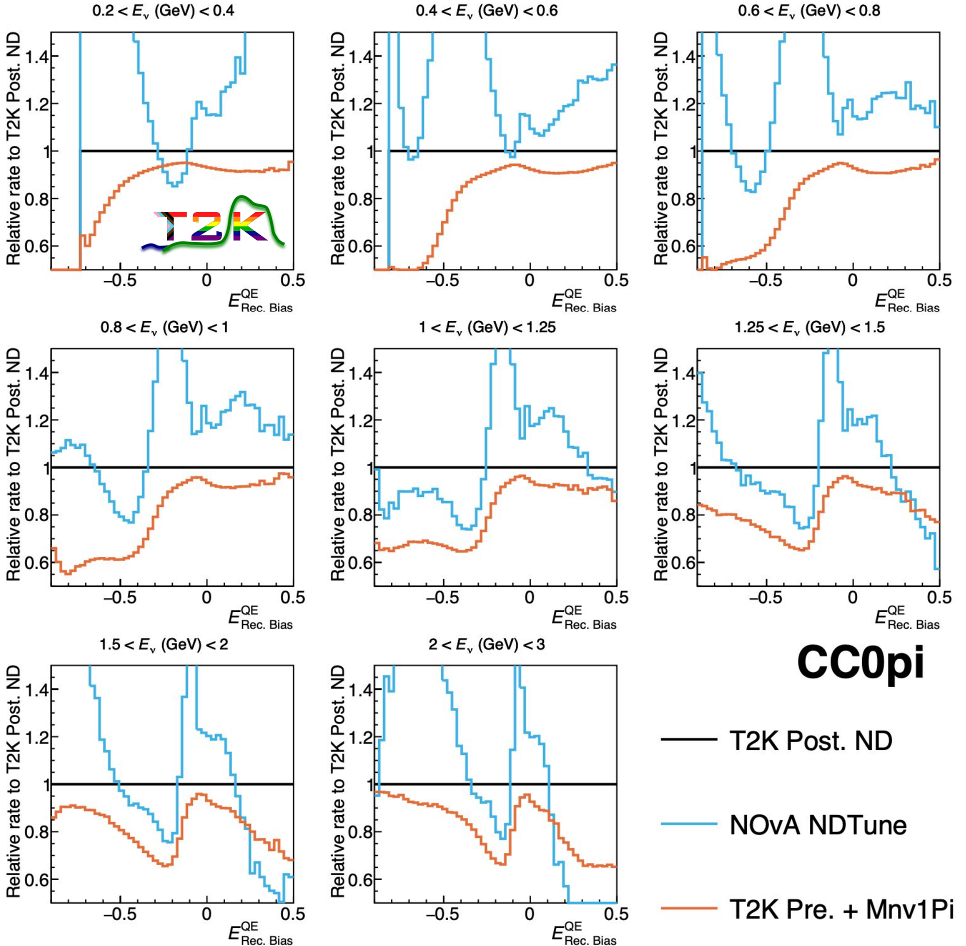


- Unable to capture all degrees of freedom. This is anticipated.

Fake Data Effects on ERec



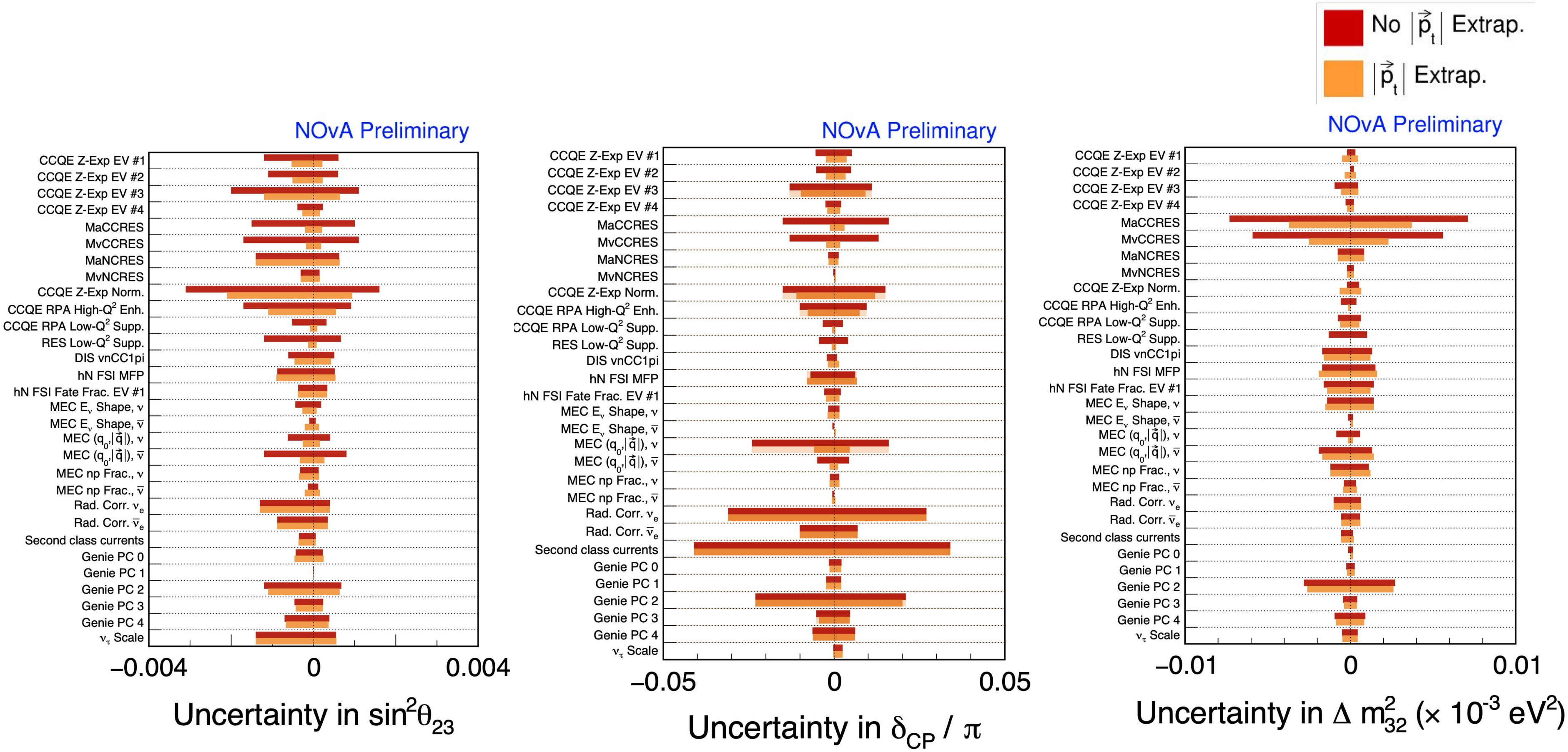


Outlook

- A joint analysis with a combined systematic model is difficult!
- There are intrinsic differences and *ad hoc* modeling freedom, different energies, different detectors can mean equivalent xsec parameters are not simply relatable
- Simulated fake data generation can be improved via multivariate MC reweighting with BDTs/Other ML algorithms
- Needs generator models to cover large phase space to make reweighting possible
- Current measurements are still statistically limited:
  - Constraints on important nuisance parameters are not too strong
  - Fake Data Studies can identify shortcomings in systematics modeling
- DUNE and Hyper-K measurements will not be statistically limited
  - We need to make the modeling and tooling connections as compatible as possible by the time the next generation of experiment takes data

Backups

NOvA Systematics



T2K Systematics

Parameter	Pre-fit	Post-fit	Comment
M_A^{QE} (GeV/c^2)	1.03 ± 0.06	1.17 ± 0.04	
$Q^2 < 0.05$ GeV^2	$1.00 \pm \infty$	0.78 ± 0.05	Norm. on true CCQE events in true Q^2.
$0.05 < Q^2 < 0.10$ GeV^2	$1.00 \pm \infty$	0.89 ± 0.04	
$0.10 < Q^2 < 0.15$ GeV^2	$1.00 \pm \infty$	1.03 ± 0.05	
$0.15 < Q^2 < 0.20$ GeV^2	$1.00 \pm \infty$	1.03 ± 0.08	
$0.20 < Q^2 < 0.25$ GeV^2	$1.00 \pm \infty$	1.09 ± 0.10	
$0.25 < Q^2 < 0.50$ GeV^2	1.00 ± 0.11	1.26 ± 0.06	
$0.50 < Q^2 < 1.00$ GeV^2	1.00 ± 0.18	1.14 ± 0.08	
$Q^2 > 1.00$ GeV^2	1.00 ± 0.40	1.26 ± 0.14	
$\Delta E^C_{rmv} \nu$ (MeV)	2.00 ± 6.00	-2.38 ± 1.75	
$\Delta E^C_{rmv} \bar{\nu}$ (MeV)	0.00 ± 6.00	1.64 ± 1.93	
$\Delta E^O_{rmv} \nu$ (MeV)	4.00 ± 6.00	2.55 ± 3.08	
$\Delta E^O_{rmv} \bar{\nu}$ (MeV)	0.00 ± 6.00	-1.26 ± 3.19	
2p2h norm. ν	$1.00 \pm \infty$	1.06 ± 0.15	
2p2h norm. $\bar{\nu}$	$1.00 \pm \infty$	0.72 ± 0.16	
2p2h norm. C$\to$O	1.00 ± 0.20	1.05 ± 0.15	
2p2h shape C	0.00 ± 3.00	0.97 ± 0.46	-1 is non-Δ-like, 0 is Nieves *et al.* [59], +1 is Δ-like.
2p2h shape O	0.00 ± 3.00	0.00 ± 0.17	
2p2h low-E_ν ν	1.00 ± 1.00	1.00 ± 1.00	+1 is Nieves-like [59], 0 is Martini-like [95]. Not fit at ND.
2p2h high-E_ν ν	1.00 ± 1.00	1.00 ± 1.00	
2p2h low-E_ν $\bar{\nu}$	1.00 ± 1.00	1.00 ± 1.00	
2p2h high-E_ν $\bar{\nu}$	1.00 ± 1.00	1.00 ± 1.00	
C_5^A	0.96 ± 0.15	0.98 ± 0.06	
M_A^{RES} (GeV/c^2)	1.07 ± 0.15	0.79 ± 0.05	
$I_{1/2}$ non-res norm. low-p_π $\bar{\nu}_\mu$	0.96 ± 0.96	0.96 ± 0.96	Not fit at ND.
$I_{1/2}$ non-res norm.	0.96 ± 0.40	0.87 ± 0.23	
CC coh. C norm.	1.00 ± 0.30	0.61 ± 0.22	
CC coh. O norm.	1.00 ± 0.30	0.61 ± 0.22	
Coulomb corr. ν	1.00 ± 0.02	1.00 ± 0.02	
Coulomb corr. $\bar{\nu}$	1.00 ± 0.01	1.00 ± 0.01	
ν_e/ν_μ norm.	1.00 ± 0.03	1.00 ± 0.03	No ND selection, poorly constrained.
$\bar{\nu}_e/\bar{\nu}_\mu$ norm.	1.00 ± 0.03	1.00 ± 0.03	
CC Bodek-Yang on/off DIS	0.00 ± 1.00	1.04 ± 0.19	+1 is B-Y supp. off, 0 is B-Y supp. on. [70,71]
CC Bodek-Yang on/off multi-π	0.00 ± 1.00	-0.03 ± 0.18	
CC multiplicity multi-π	0.00 ± 1.00	0.14 ± 0.71	+1 is AGKY-like [112], 0 is NEUT-like.
CC misc. norm.	1.00 ± 1.00	2.28 ± 0.43	
CC DIS+multi-π norm. ν	1.00 ± 0.04	1.06 ± 0.03	
CC DIS+multi-π norm. $\bar{\nu}$	1.00 ± 0.07	0.94 ± 0.06	
NC coh. norm.	1.00 ± 0.30	1.02 ± 0.30	No ND selection, poorly constrained.
NC 1γ norm.	1.00 ± 1.00	1.00 ± 1.00	
NC other ND norm.	1.00 ± 0.30	1.66 ± 0.13	Not propagated to FD.
NC other FD norm.	1.00 ± 0.30	1.00 ± 0.30	Not fit at ND.
Pion FSI Quasi-Elastic	1.00 ± 0.29	0.83 ± 0.09	Scaling of pion scattering probabilities relative to the constraint from external data [43]
Pion FSI Quasi-Elastic $p_\pi > 500$ MeV/c	1.00 ± 0.47	0.75 ± 0.16	
Pion FSI Inelastic	1.00 ± 1.10	1.71 ± 0.31	
Pion FSI Absorption	1.00 ± 0.31	1.19 ± 0.12	
Pion FSI Charge Exchange	1.00 ± 0.44	0.78 ± 0.34	