NOvA and neutrino interaction uncertainties

on behalf of the NOvA collaboration

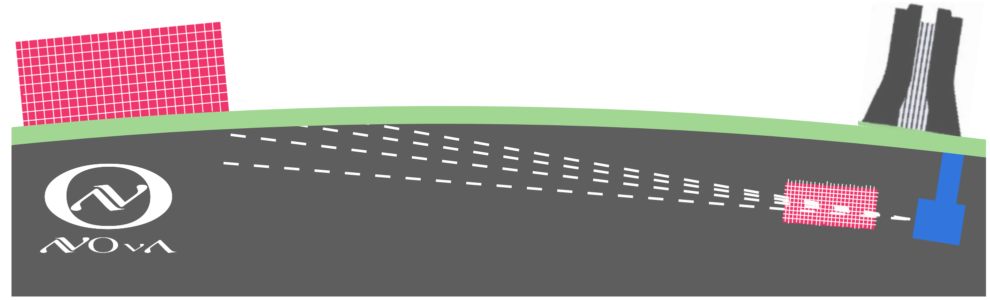
April 15, 2024

NuInt 2024

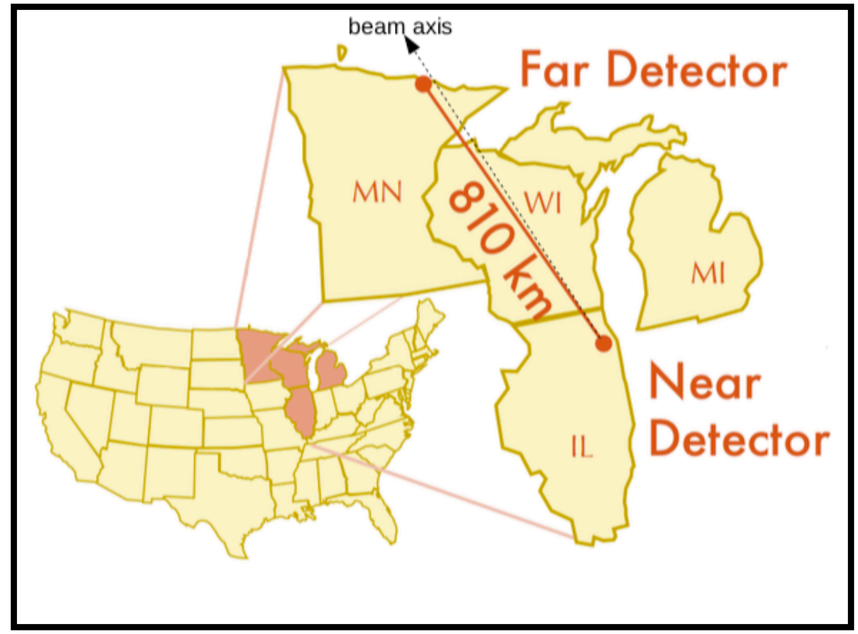
Mike Dolce

Wichita State University

NOvA Experiment



- **N**uMI **O**ff-axis ν_e **A**ppearance experiment, located at Fermilab.
- Broad physics program:
  - **oscillations** (e.g. $\Delta m^2_{32},\ \sin^2\theta_{23},$ and δ_{CP}).
  - **cross sections** (e.g. in Q^2, E_ν, E_{avail}, $|\vec{q}\,|$).
  - **non-standard interactions** (e.g. $\epsilon_{e\mu}$, $\epsilon_{e\tau}$).
  - "**exotics**" (e.g. slow monopoles, seasonal muons, supernova neutrinos).



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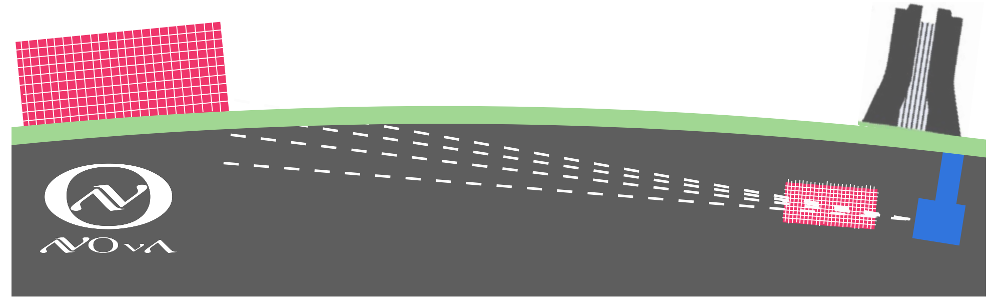

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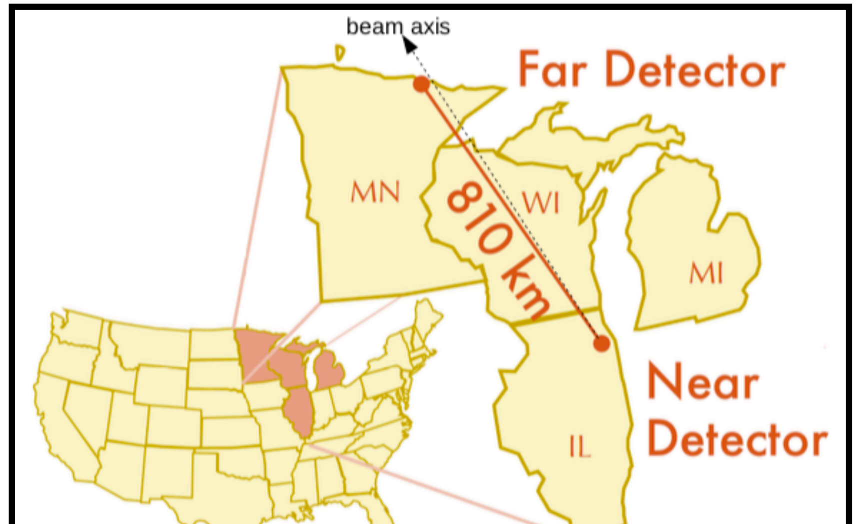
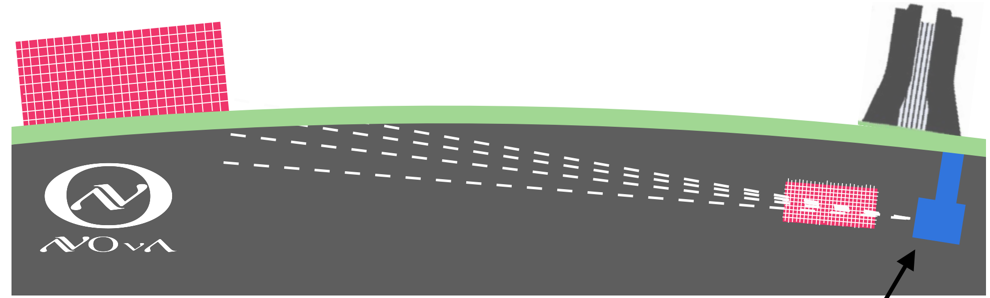


- **Goal**: Discuss the spirit of how NOvA addresses uncertainties in two broad categories:
- **Data-driven analyses:**
  - oscillations, extrapolation.
- **Model-spread analyses:**
  - cross section, 2p2h component.

NuMI Beamline

- NuMI record of 950 kW in 2023.
- ~ Several million interactions in Near Detector (ND).
- ~ Several hundred in Far Detector (FD).
- $\langle E_\nu \rangle$ ~ 2 GeV.



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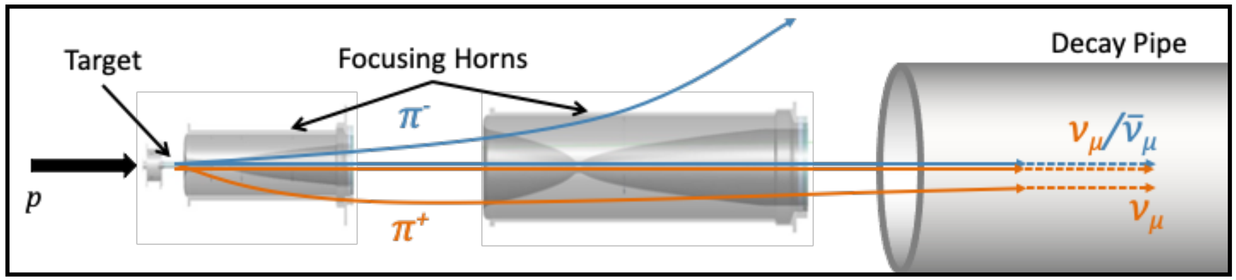
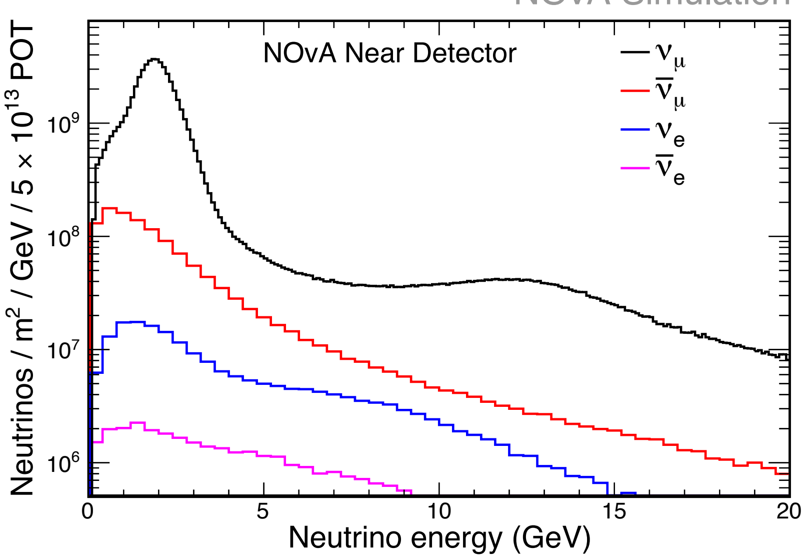
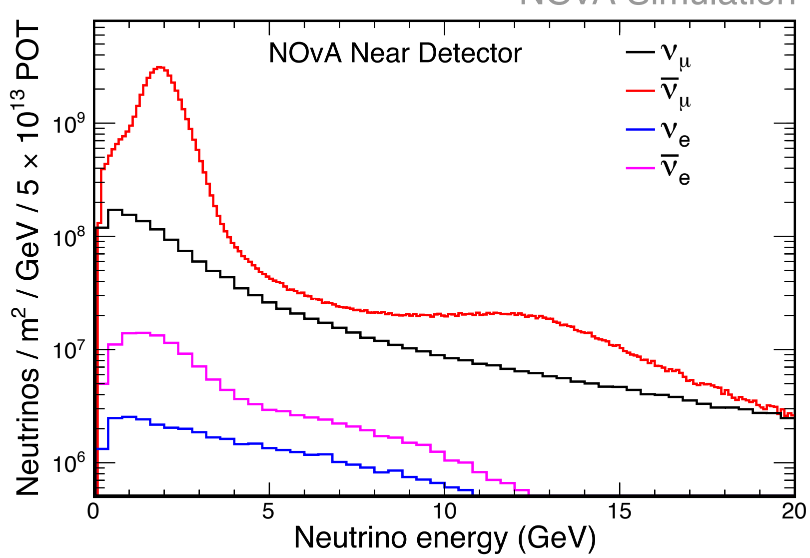


ν mode: 94% pure ν_μ

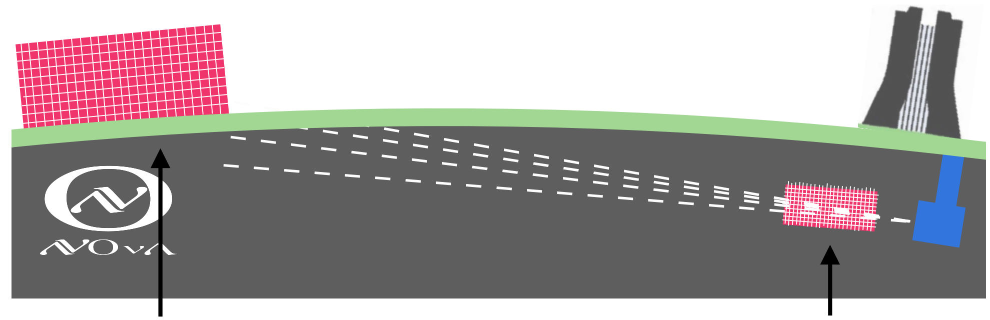


$\bar{\nu}$ mode: 92% pure $\bar{\nu}_\mu$



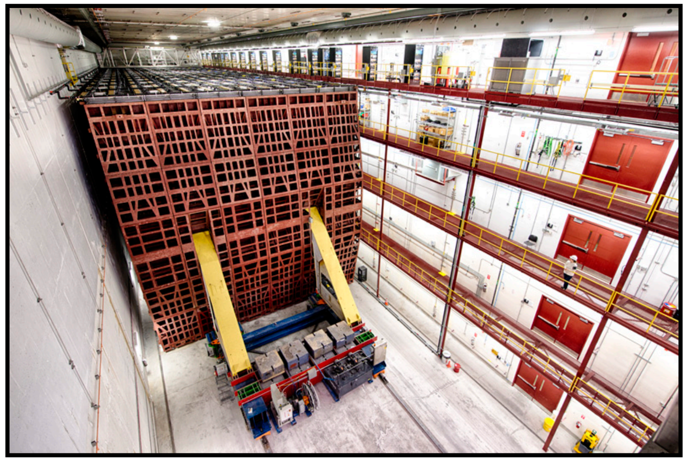
NOvA Experiment

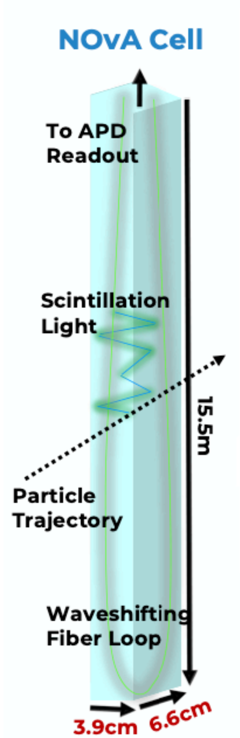
- Functionally equivalent detectors.
- PVC cells filled with liquid scintillator, arranged orthogonally for stereographic image.

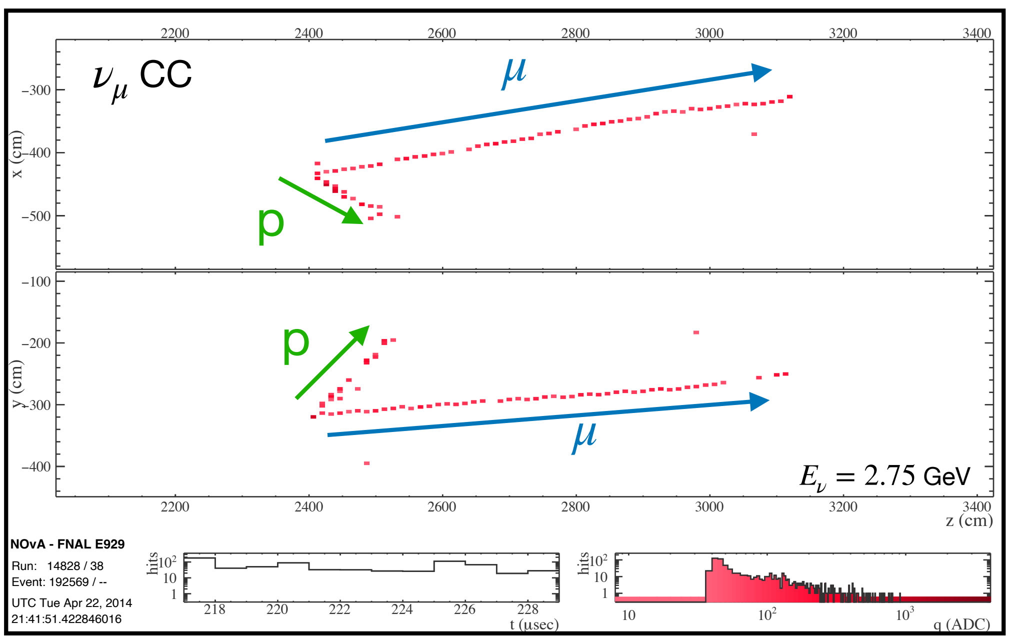


Far Detector

Near Detector

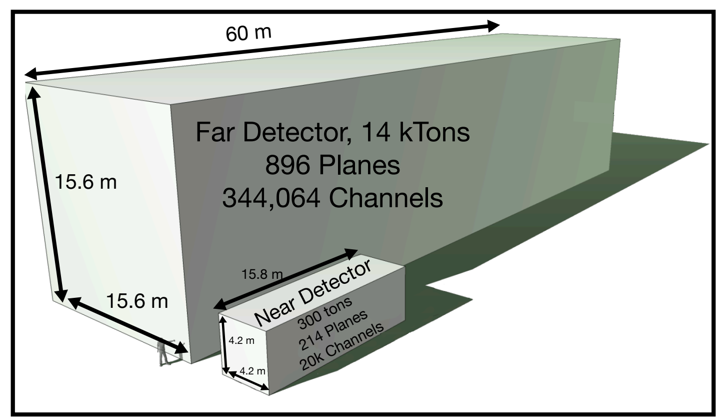




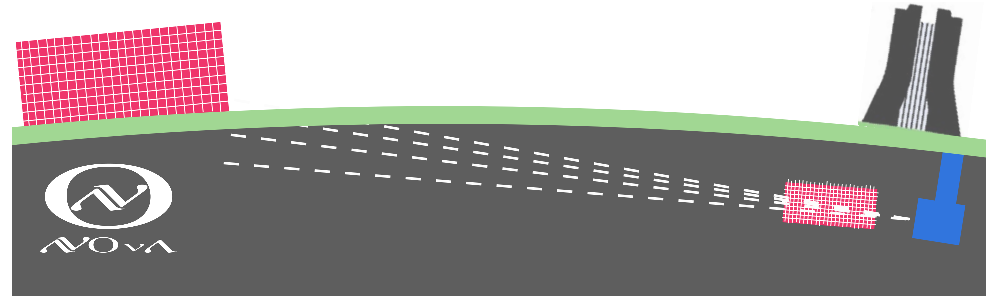


Percentage of mass

H	C	O	Cl	Ti
11%	67%	3%	16%	3%



Interaction Model



- NOvA observes various neutrino interaction processes.

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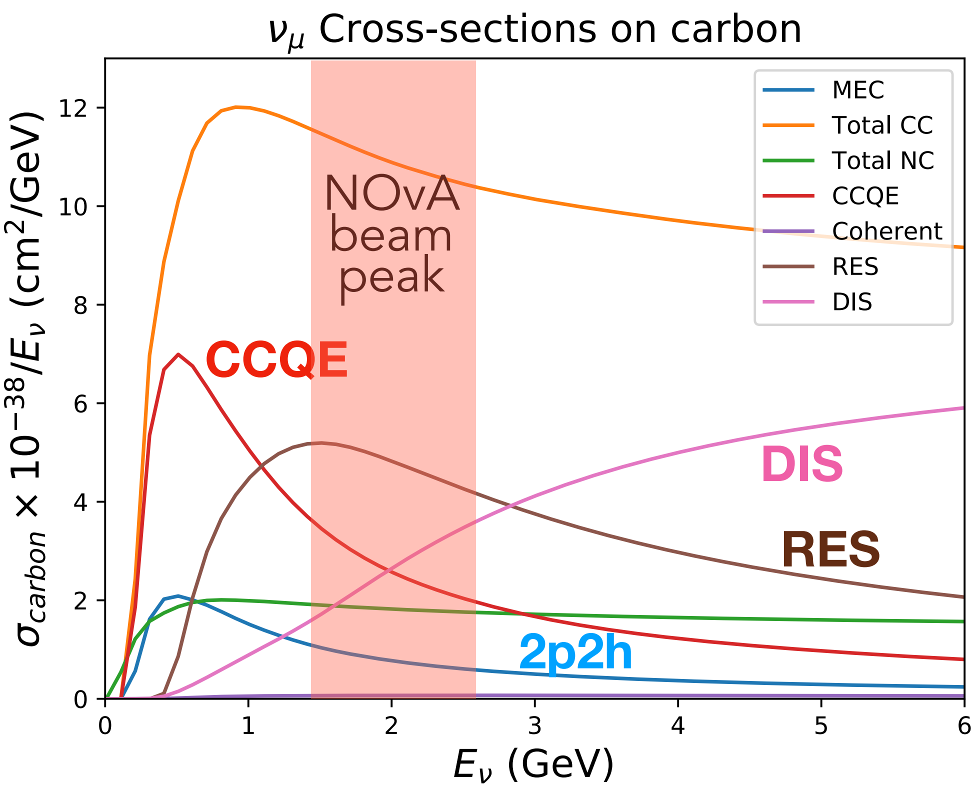
GENIE 3.0.6



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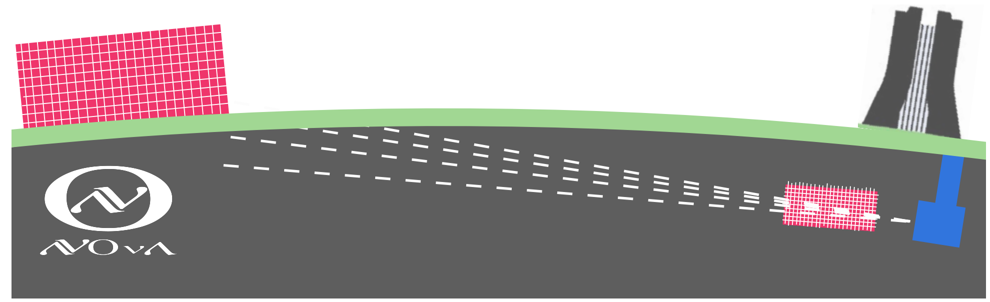
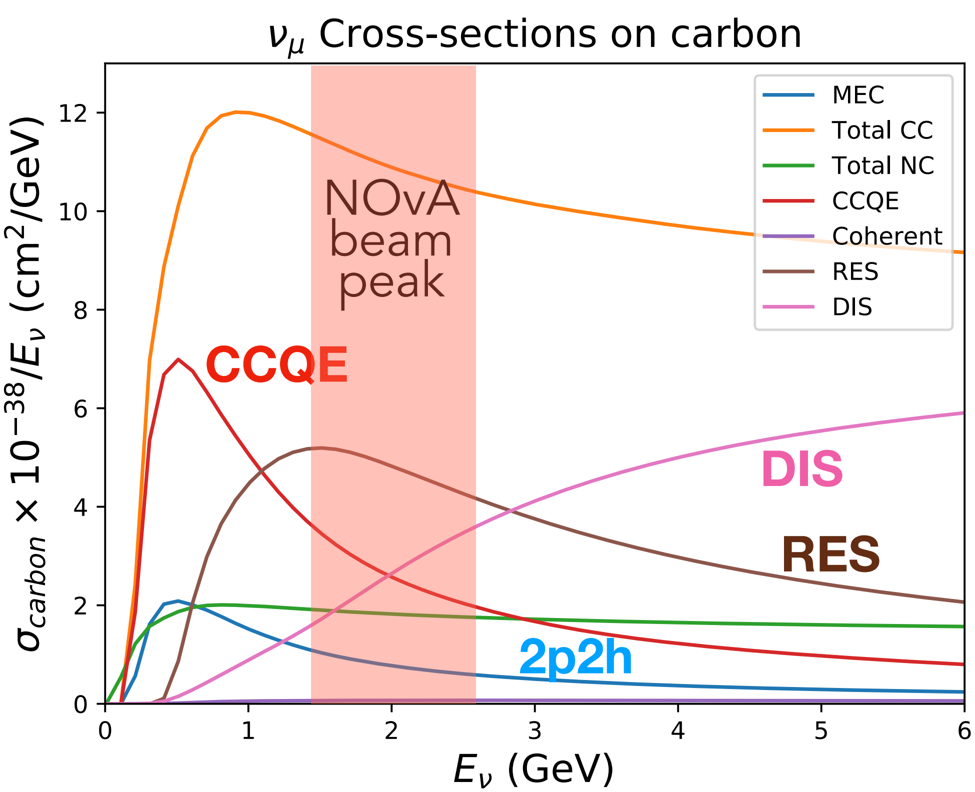


- NOvA observes various neutrino interaction processes.
- Has a custom configuration of models.



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*** custom tuning**

Process	Abbreviation	Model	Reference
Quasielastic	**QE**	Valencia 1p1h	J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C
QE Form Factor	**—**	Z-expansion	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys.
Multi-nucleon	**2p2h**	**Valencia 2p2h***	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas,
Resonance	**RES**	Berger-Seghal	Ch. Berger, L. M. Sehgal, Phys. Rev. D 76 (2007)
Deep Inelastic	**DIS**	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA
Final State Interactions	**FSI**	**hN semi-classical***	S. Dytman, Acta Physica Polonica B 40 (2009)

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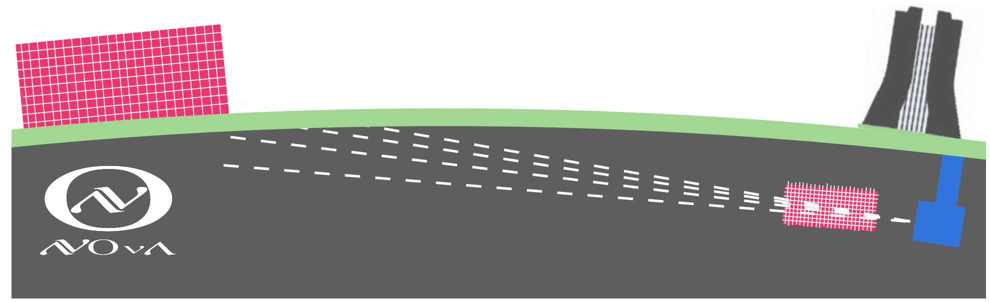

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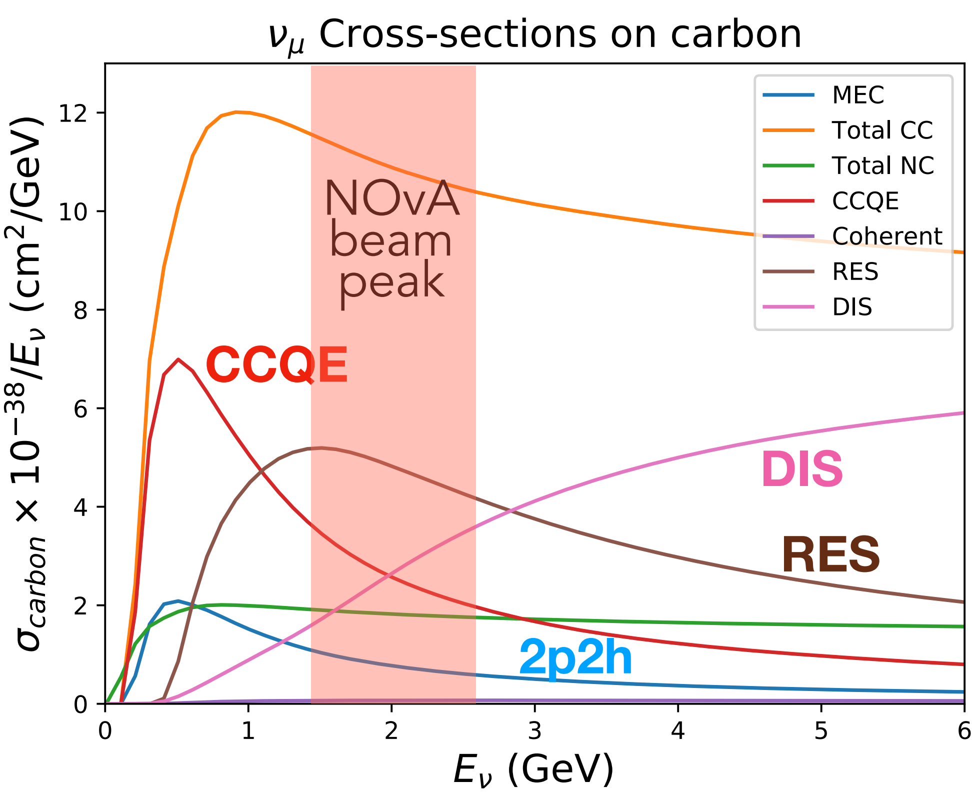

- In-house tuning of FSI and 2p2h models.
- **Focus on 2p2h — and its uncertainty treatment.**
- Elsewhere, we rely on GENIE uncertainties.

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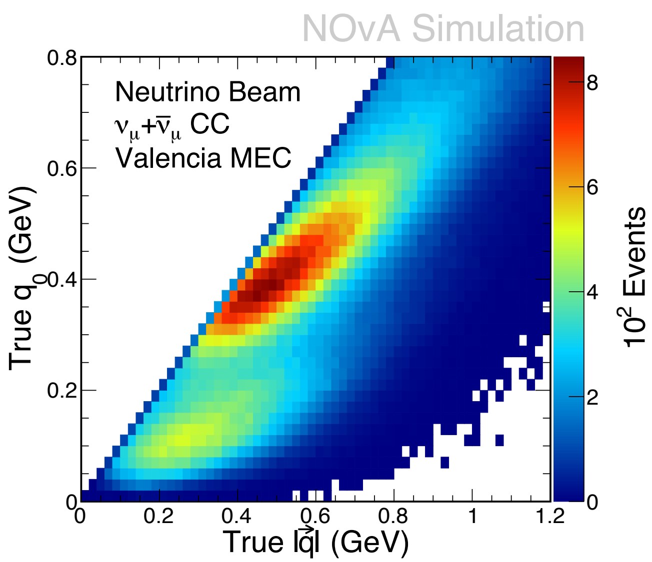
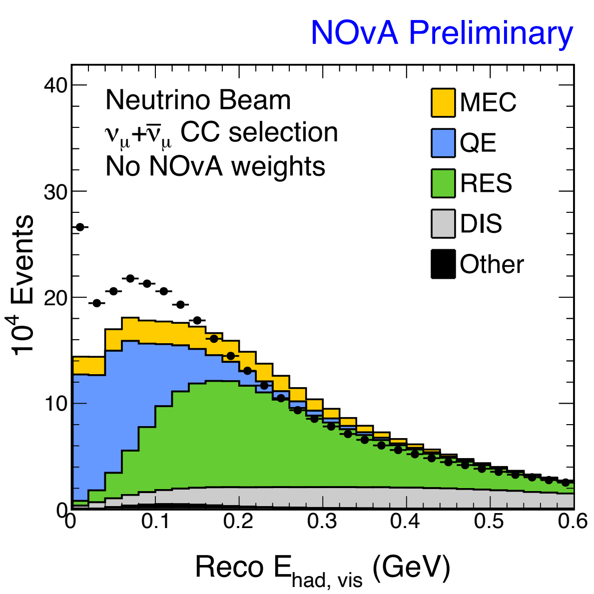
NOvA 2p2h tune

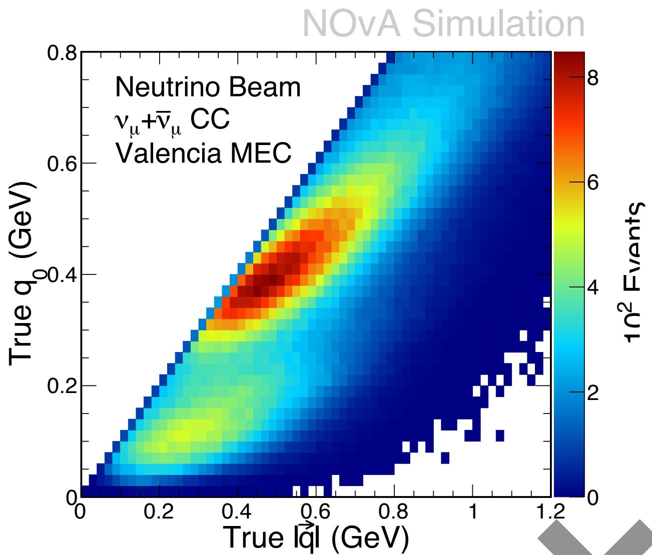
- Raw Valencia 2p2h model is insufficient with NOvA ND data.

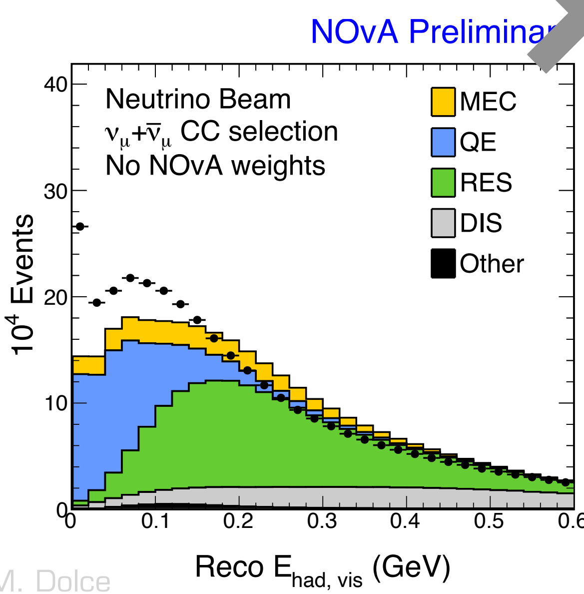


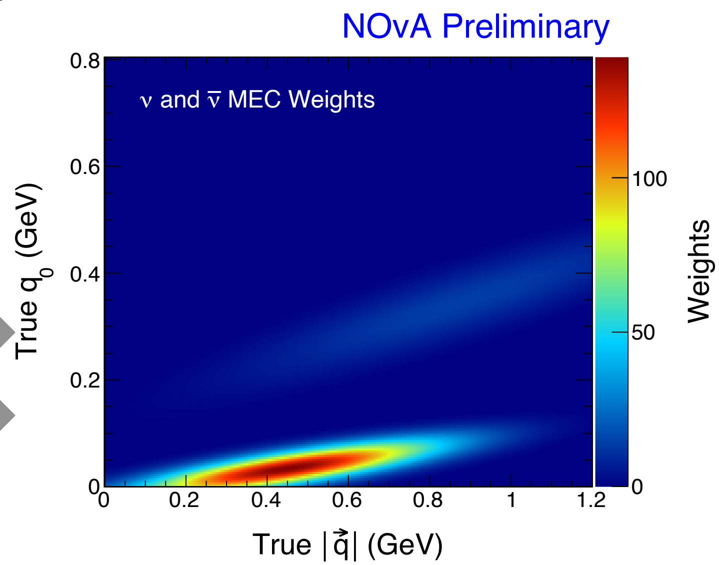


NOvA 2p2h tune

- Tune a double-Gaussian distribution in true $(|\vec{q}|, q_0)$ space to agree with ND data — "NOvA 2p2h tune".







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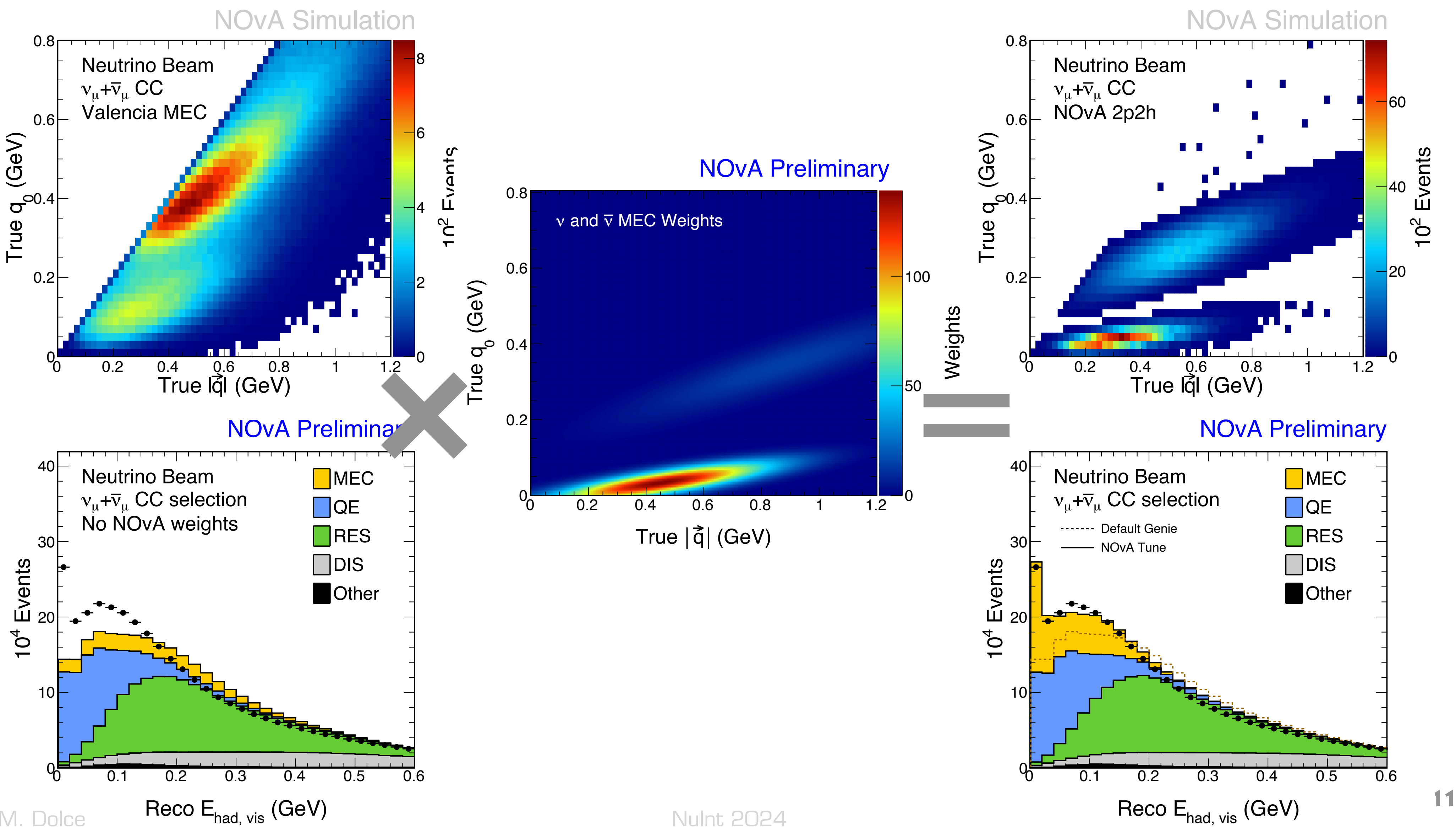
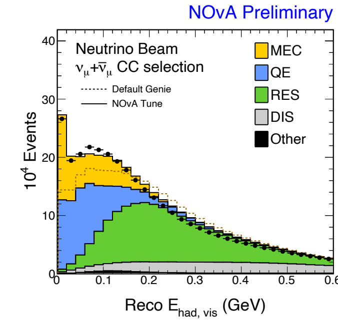
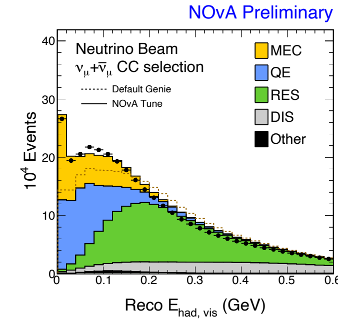




Uncertainty for 2p2h tune

- We want to have systematic freedom to account for disagreement in other channels.
- We bracket our tune with two predictions: "QE-like" & "RES-like" *.

Uncertainty for 2p2h tune



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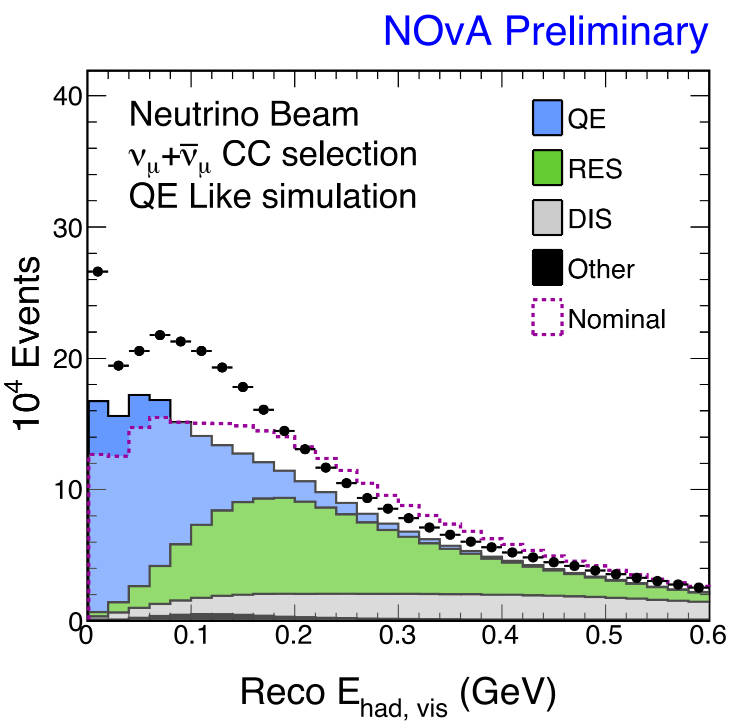

- **QE**-dominated prediction.
- Re-tune 2p2h (prev. slide) to agree with data.
- This is our "QE-like" uncertainty on 2p2h.

Systematic	Units of σ QE-like	Units of σ RES-like
Z-expansion CCQE	1	-1
Z-expansion coefficients	1	-1
CCQE RPA suppression	1	-1
CCQE RPA enhancement	1	-1
RES M_V	-1	1
RES M_A	-1	1
RES low-Q^2 suppression:	1	-1

*** NOT our only treatment, other MEC uncertainties in backup.**

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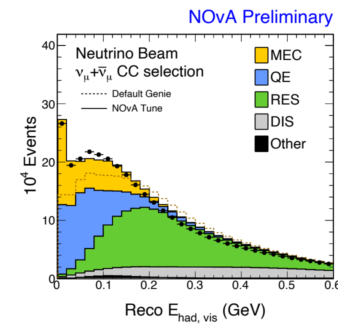

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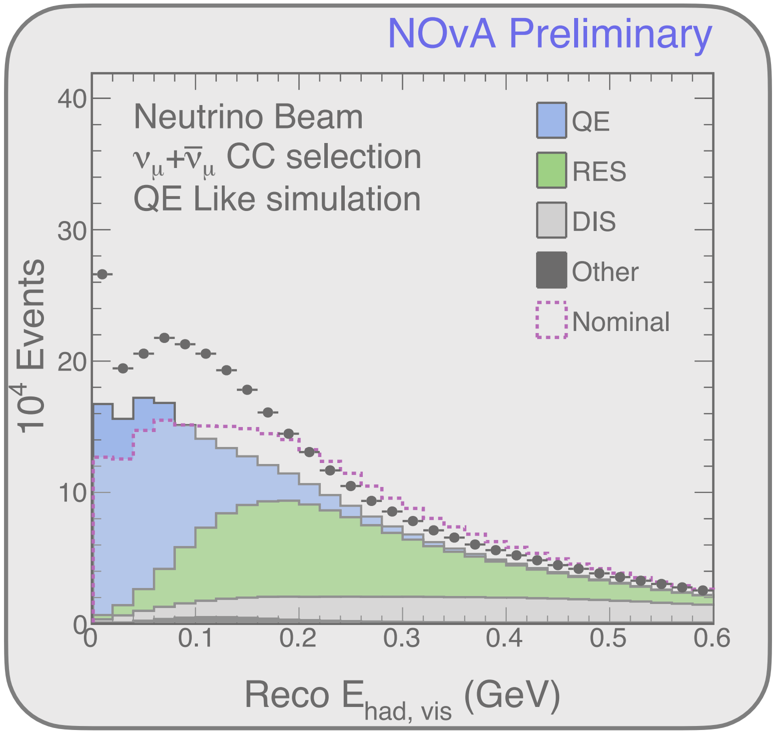

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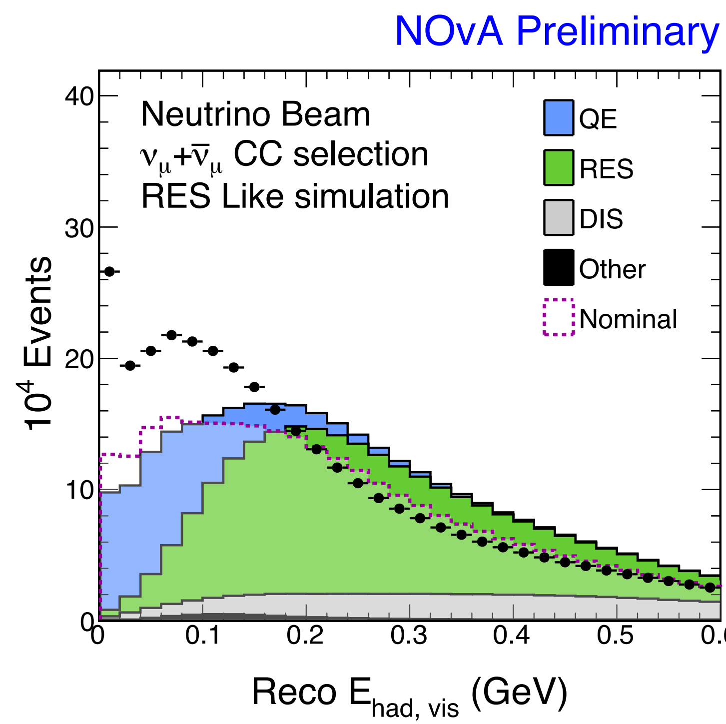

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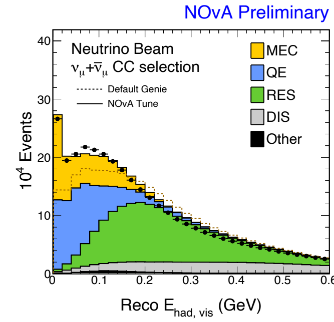
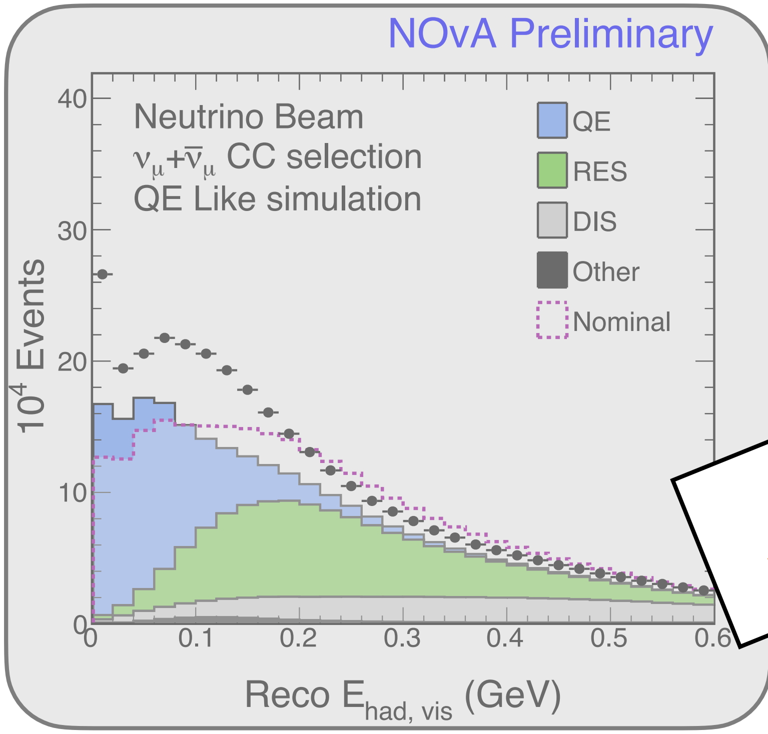
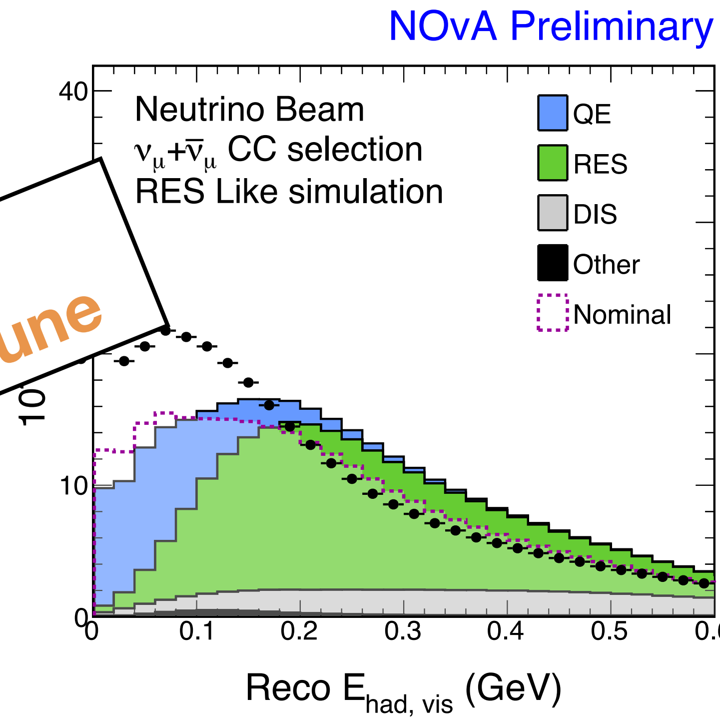




- ~~QE~~ **RES**-dominated prediction.
- Re-tune 2p2h (… slide) to … our "~~QE~~ RES-like" uncertainty on 2p2h.

This uncertainty brackets our 2p2h tune



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Oscillation analysis

Extrapolation

- NOvA can maximize the information from both detectors.
- A **data-driven approach**:
  - 1. adjust the ND prediction to agree with data.
  - 2. “extrapolate” the modified ND prediction to create FD predictions.
- Extrapolation helps correct for effects we understand — e.g. detector, geometry, beam divergence.

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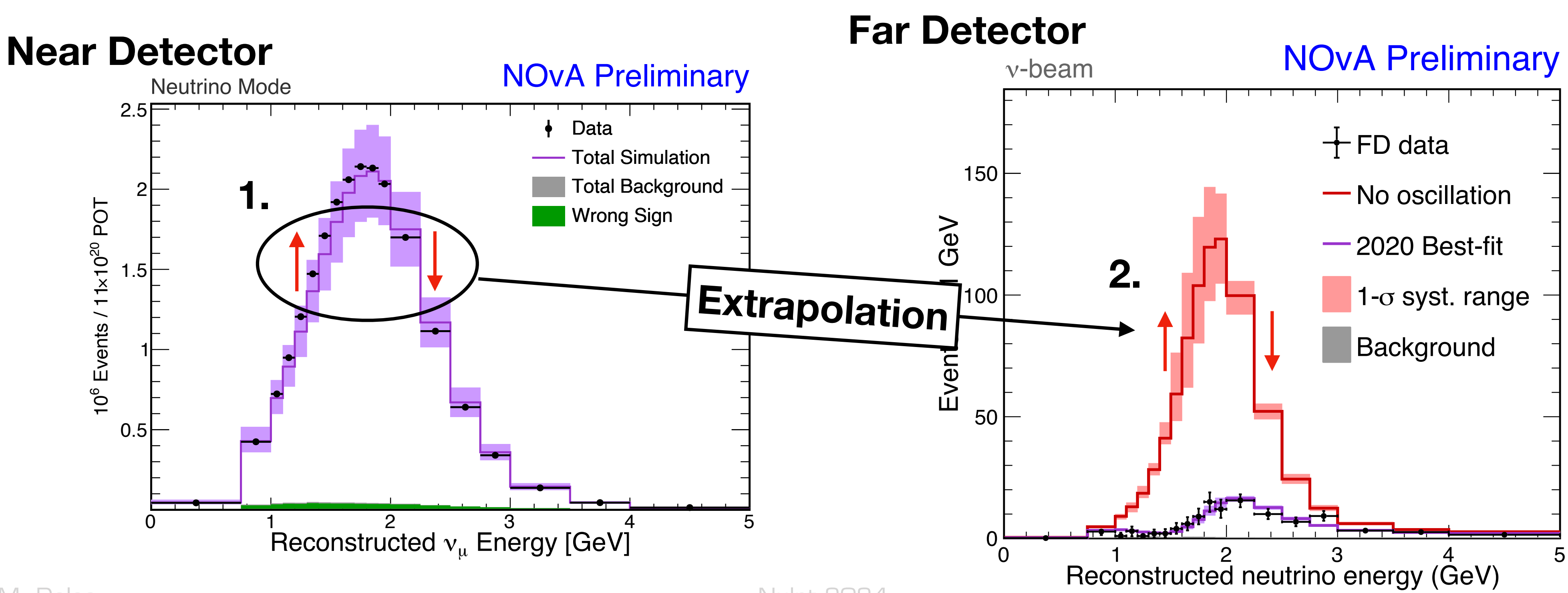

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start:
FD prediction

goal:
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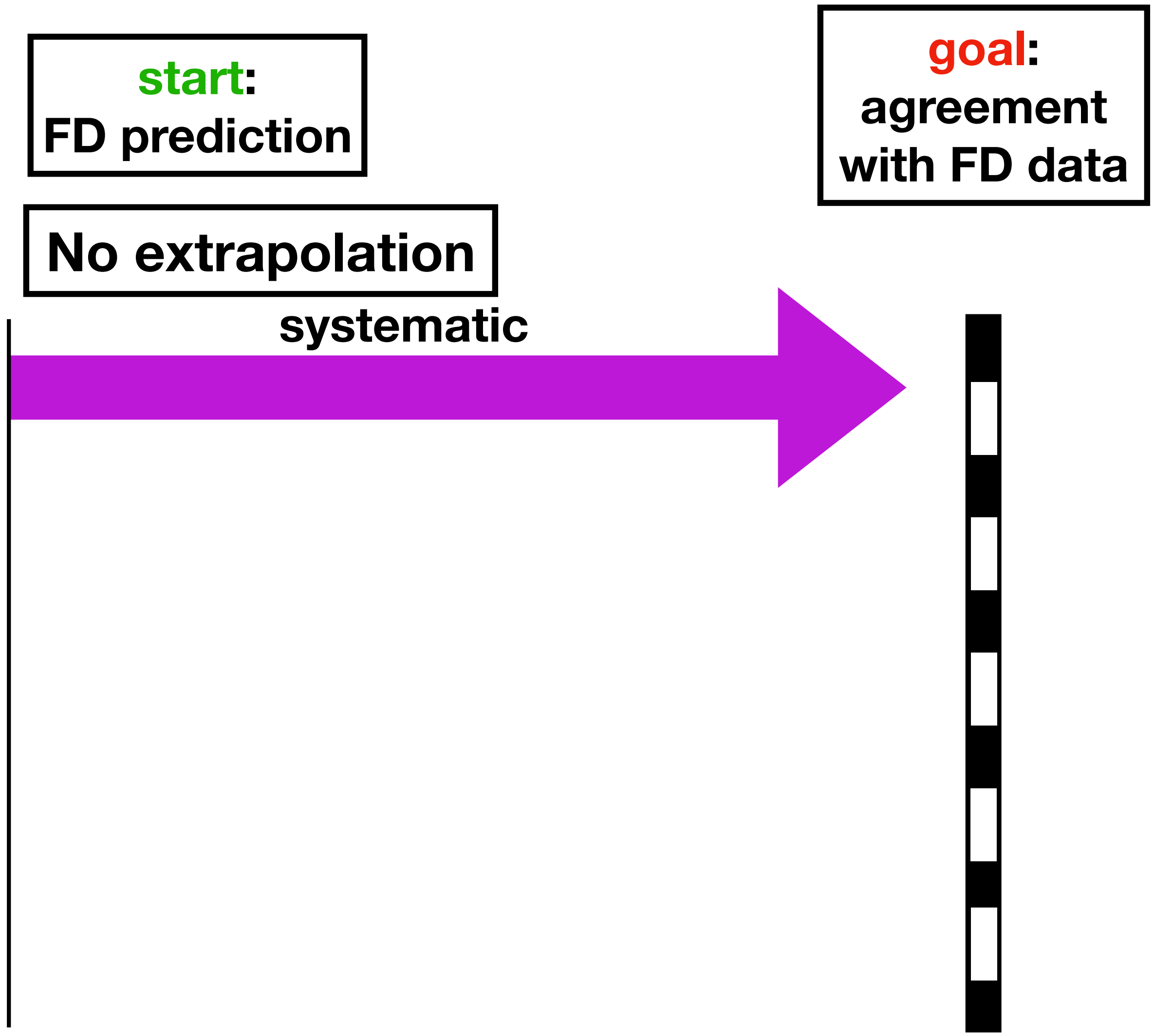

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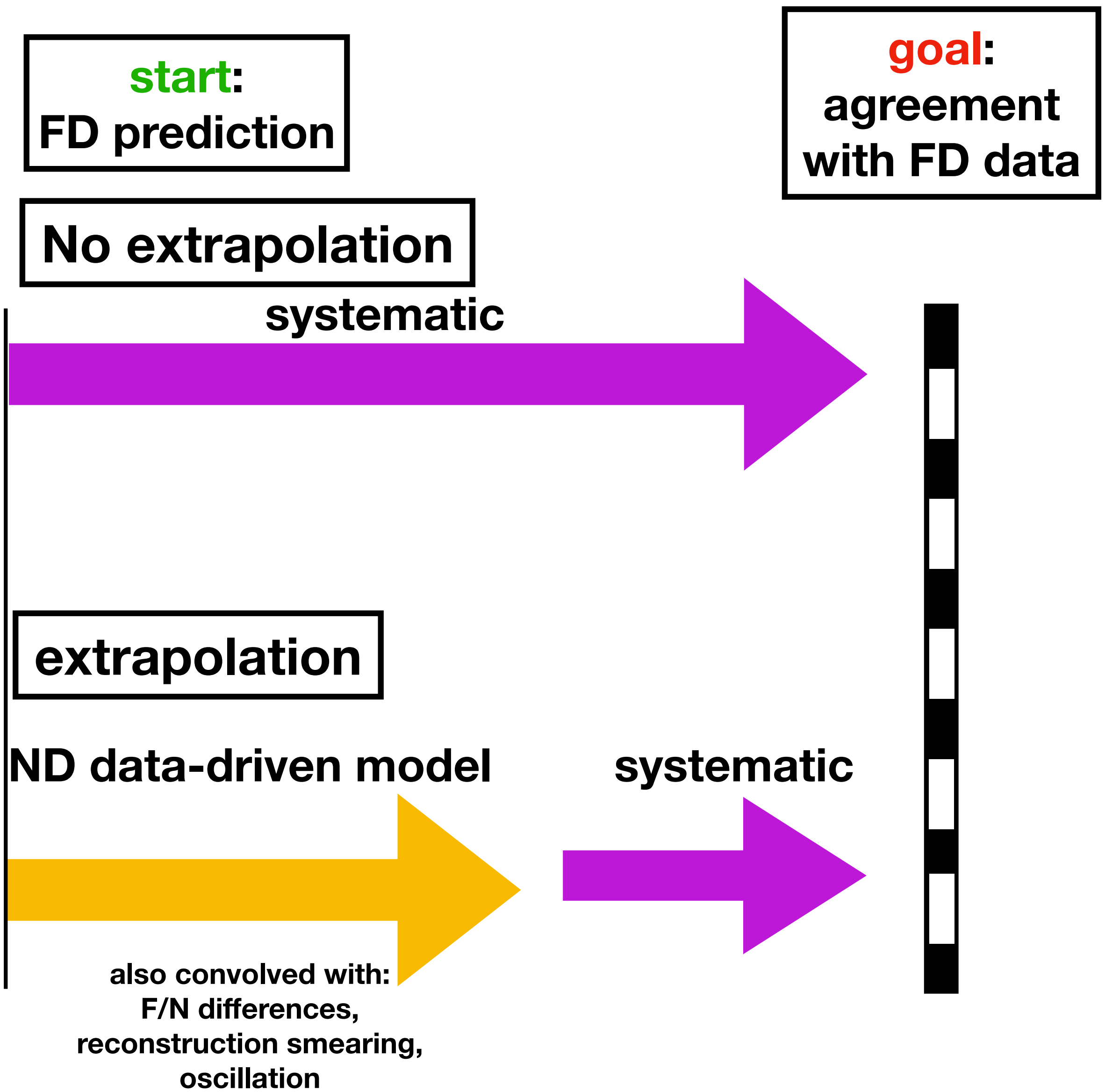

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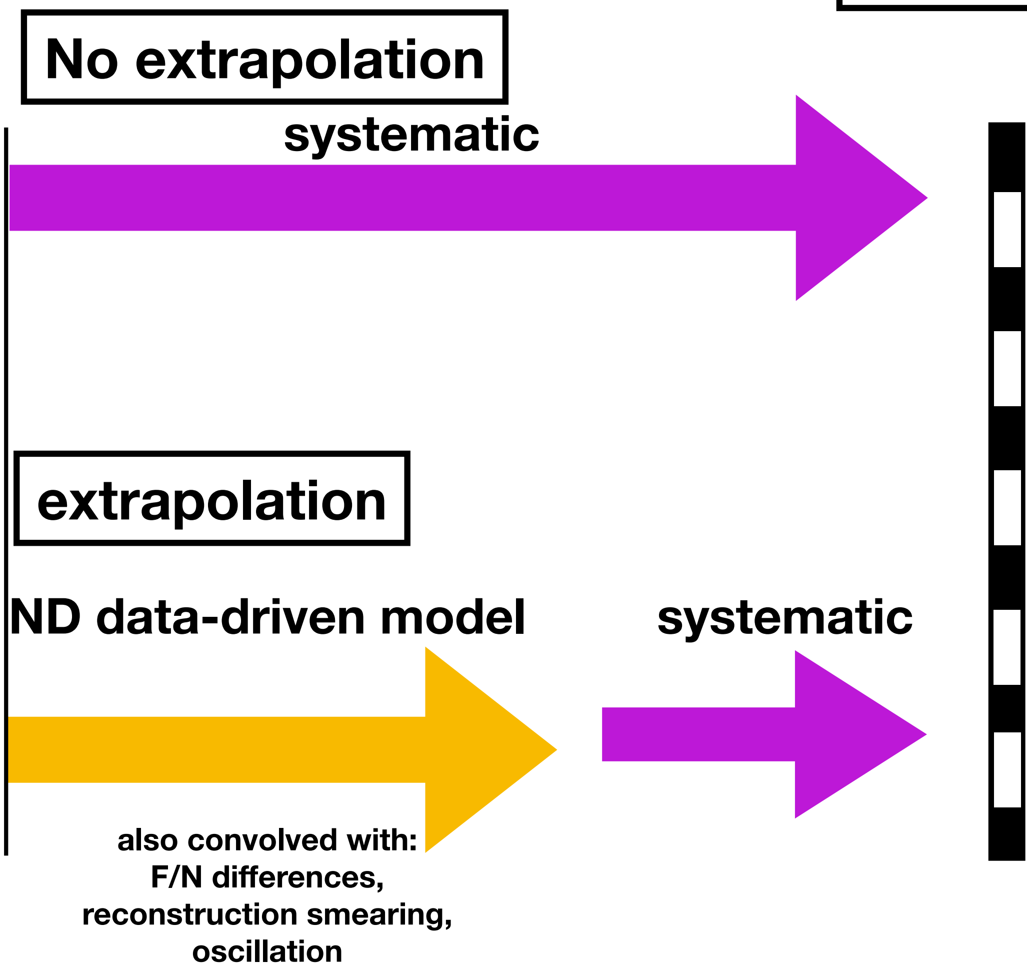
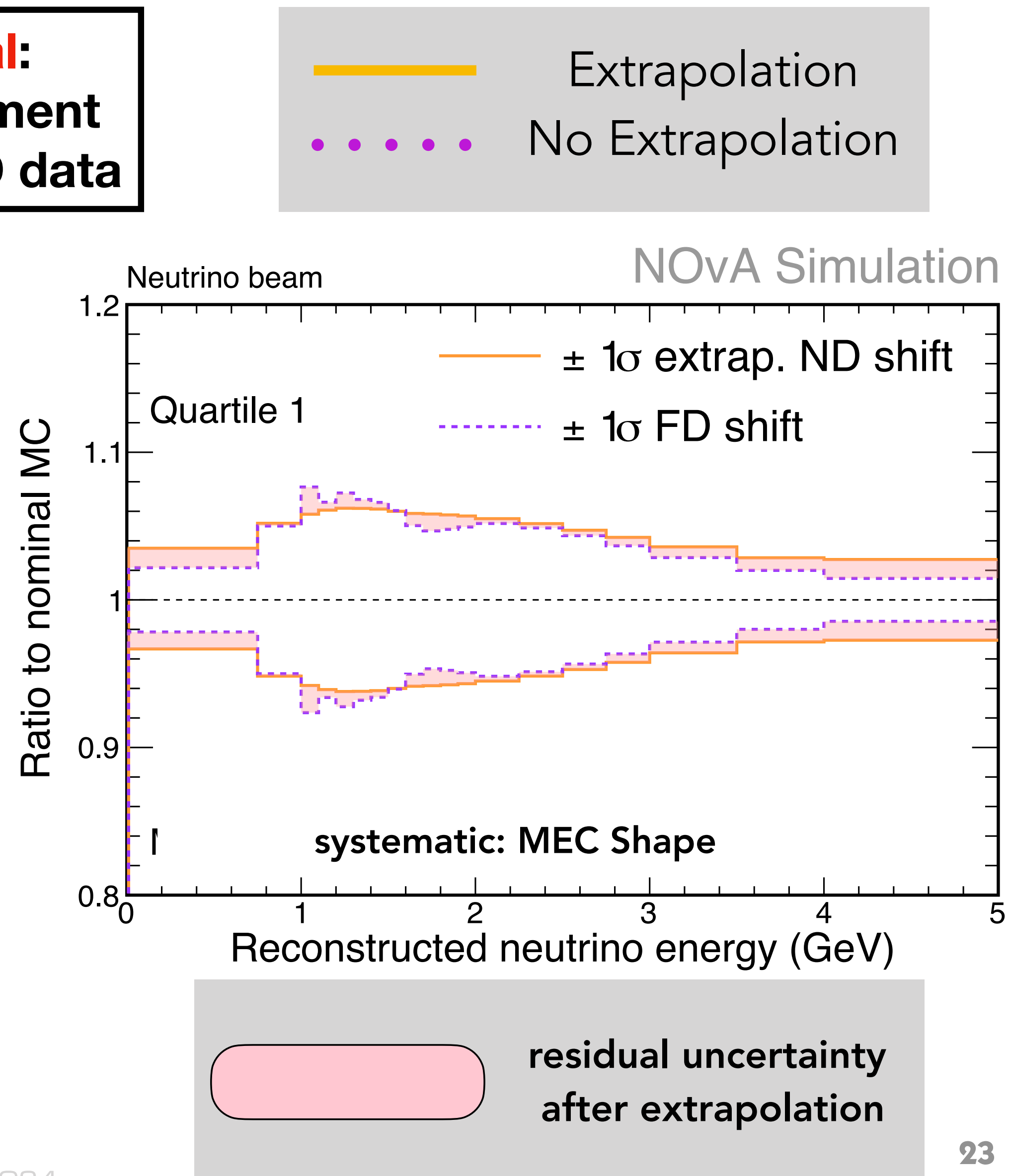
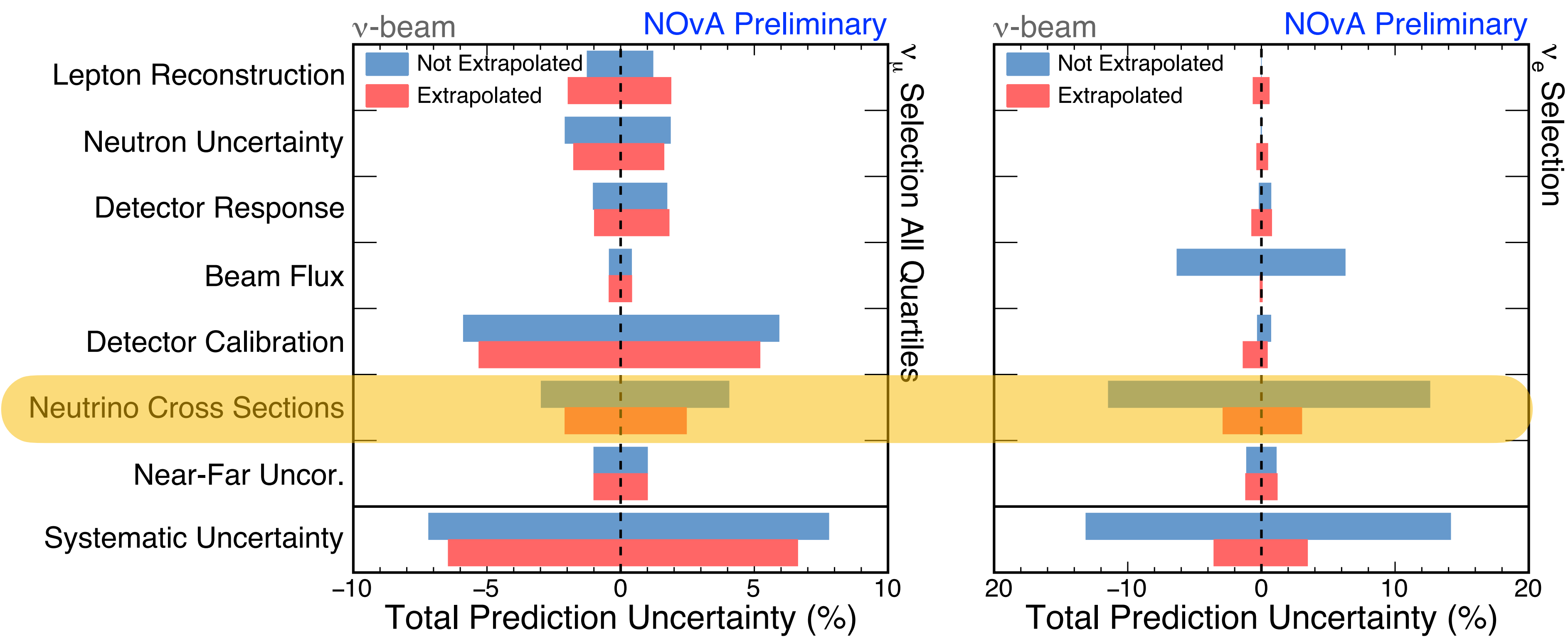




Impact of extrapolation

- Impact of extrapolation on NOvA's ν_μ and ν_e predictions.
- **Extrapolation reduces impact of cross section uncertainties**.
- Interaction uncertainties are not the leading contributor to uncertainty budget.



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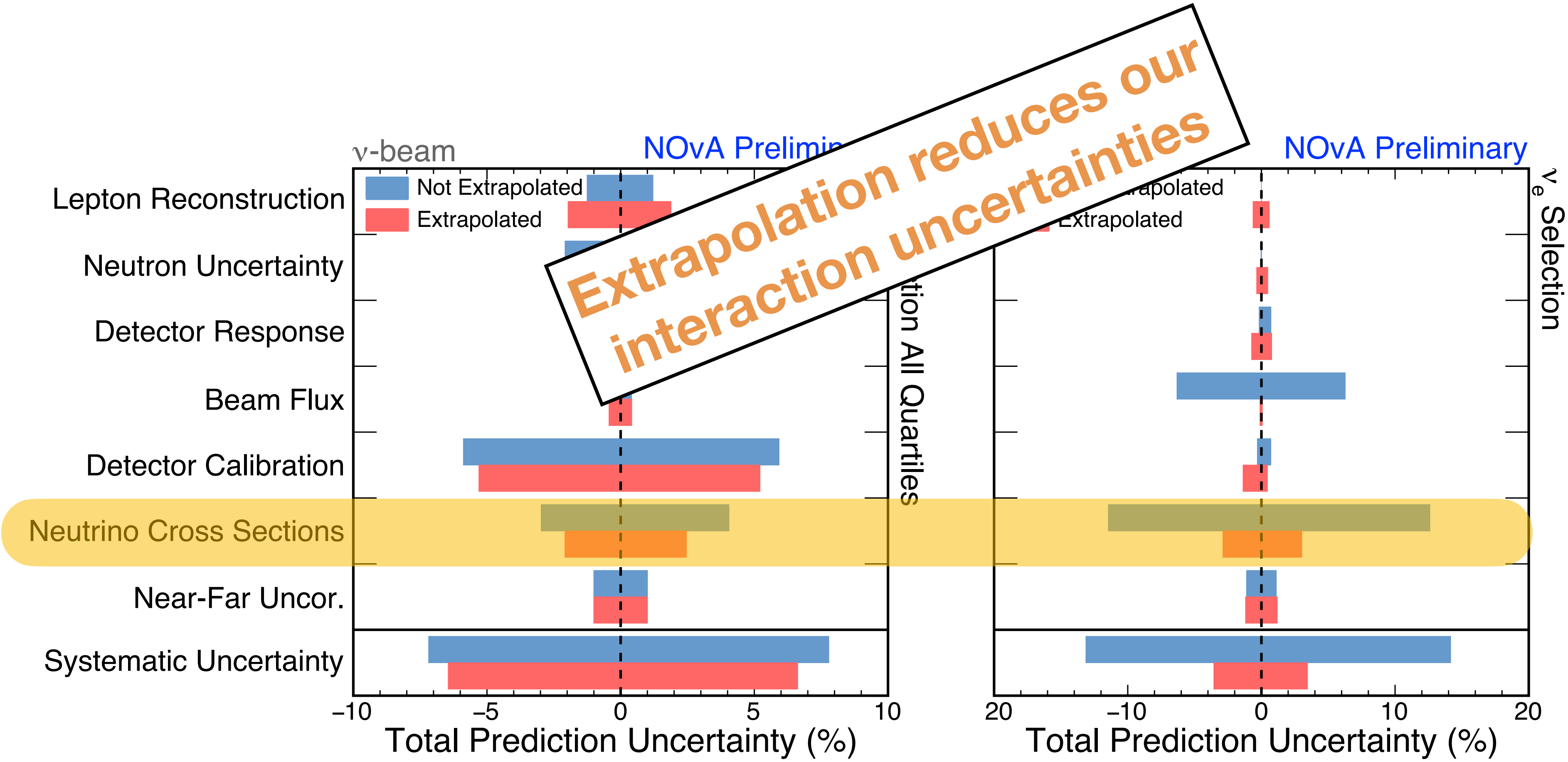
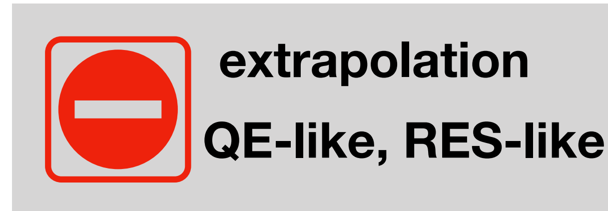
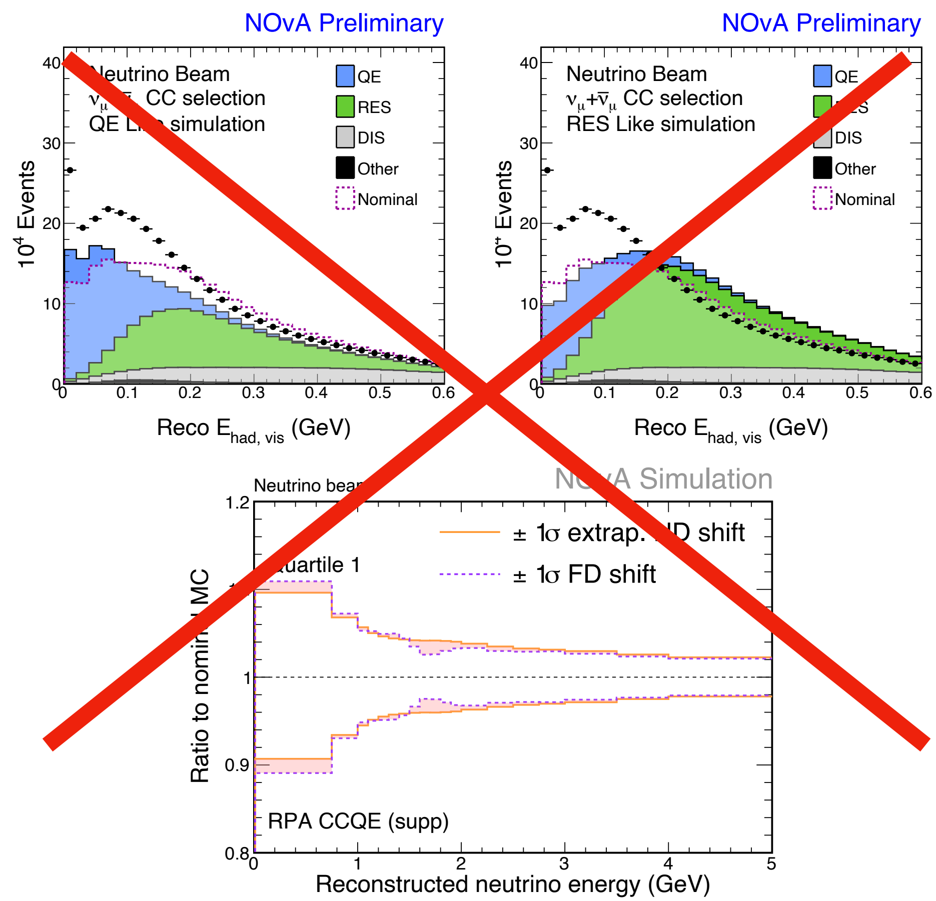


Model spread analyses

Model spread analyses

- These analyses **cannot** use two detectors to **extrapolate and mitigate interaction uncertainties**.
- Some analyses **cannot use** "QE-like" and "RES-like" uncertainties.
- An example that cannot use either:
  - ν_μ CC Low E_{had} analysis.
    - **Risk**: using ND data to tune 2p2h and then measure the same process.
    - **Opt for a model spread uncertainty.**





Model spread analyses

ν_μ CC Low-E_{had}

Differential T_μ and $\cos\theta_\mu$

select: 1 track

$T_p \leq 250$ **MeV**

$T_\pi \leq 175$ **MeV**

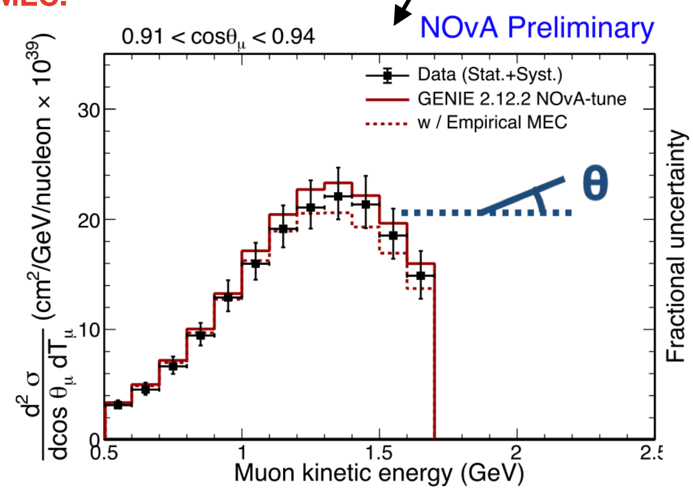
Similar NOvA 2p2h approach, different model**: Empirical MEC.**

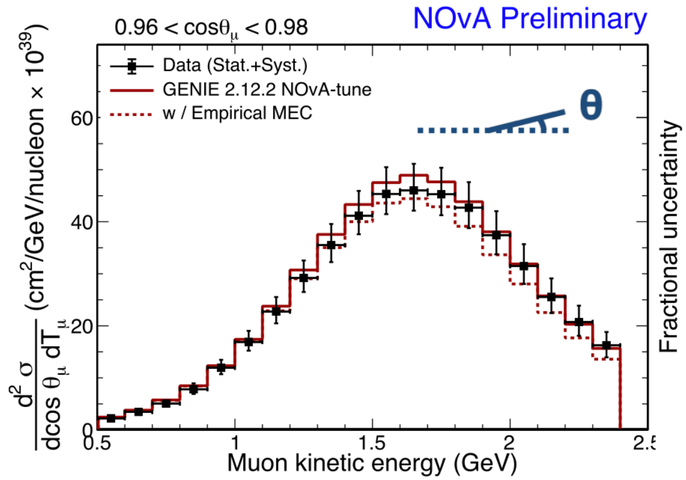
Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

- Double differential cross section in muon kinematics: $\cos\theta_\mu$, T_μ.
- MC uses NOvA 2p2h tune.

Two slices of θ_μ





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- 2p2h model spread, ~2% difference:
  - MINERvA tune (Valencia) and SuSA-v2.

2p2h model spread uncertainty

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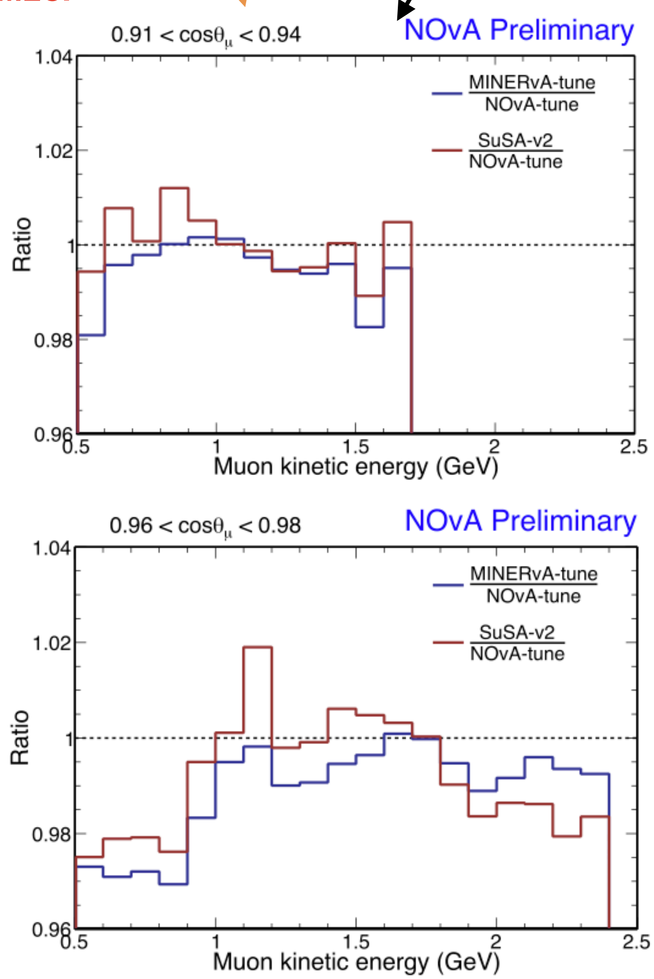

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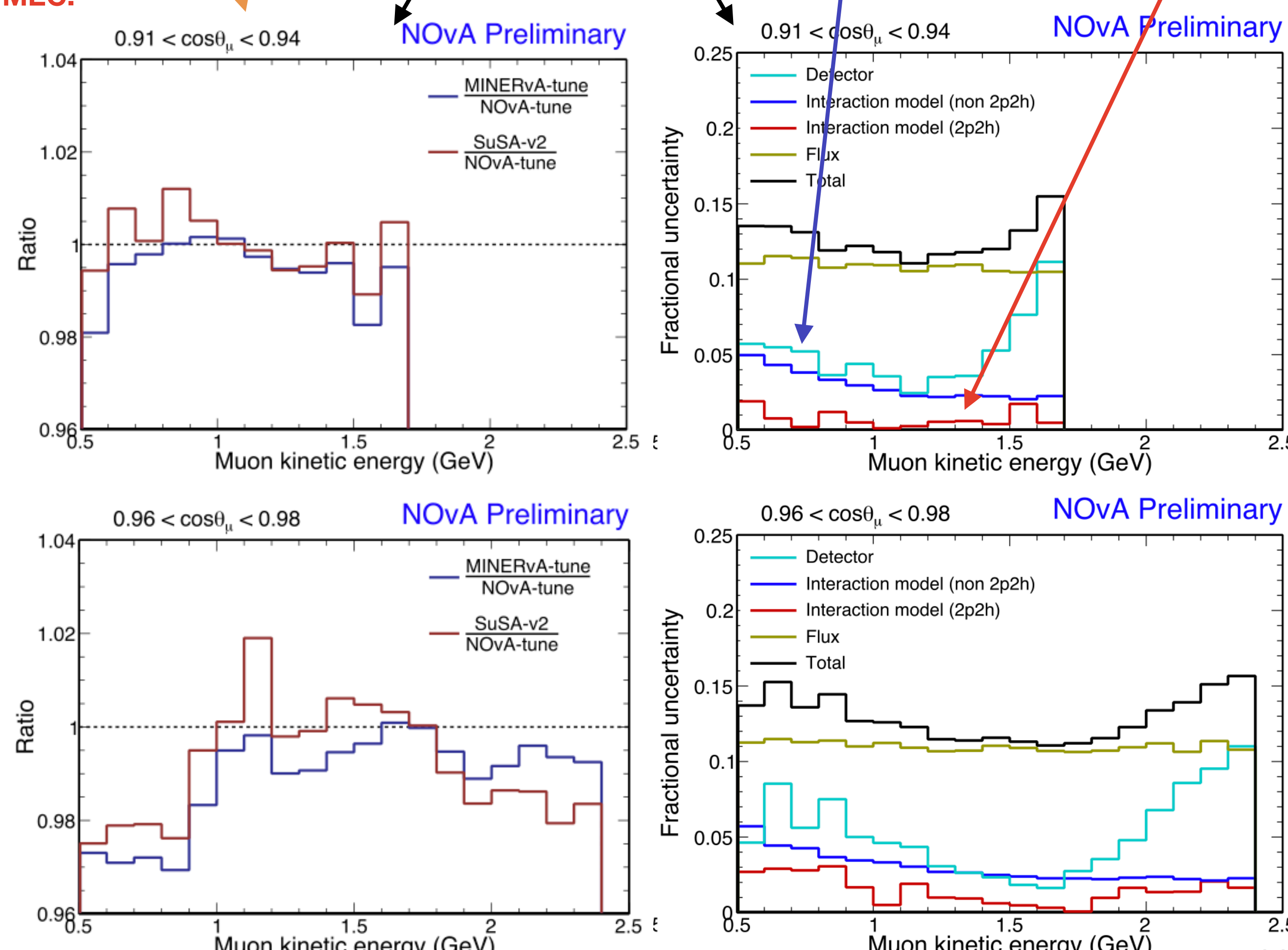
Interaction model uncertainty (non 2p2h)

Interaction model uncertainty (2p2h)



Model spread analyses

ν_μ CC Low-E_{had}

Differential T_μ and $\cos\theta_\mu$

select: 1 track

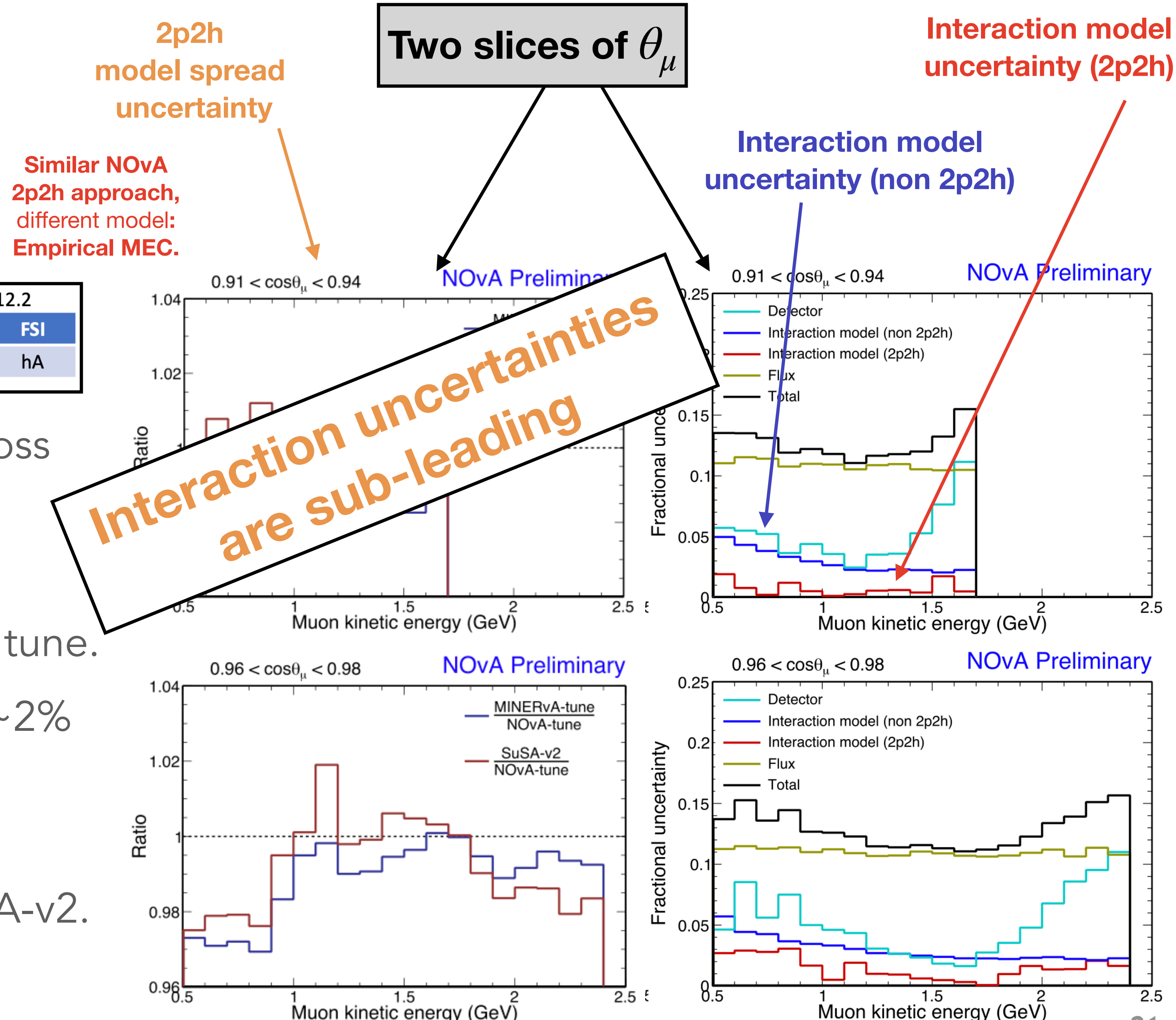
$T_p \leq 250$ **MeV**

$T_\pi \leq 175$ **MeV**

Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

- Double differential cross section in muon kinematics: $\cos\theta_\mu$, T_μ.
- MC uses NOvA 2p2h tune.
- 2p2h model spread, ~2% difference:
  - MINERvA tune (Valencia) and SuSA-v2.



Summary

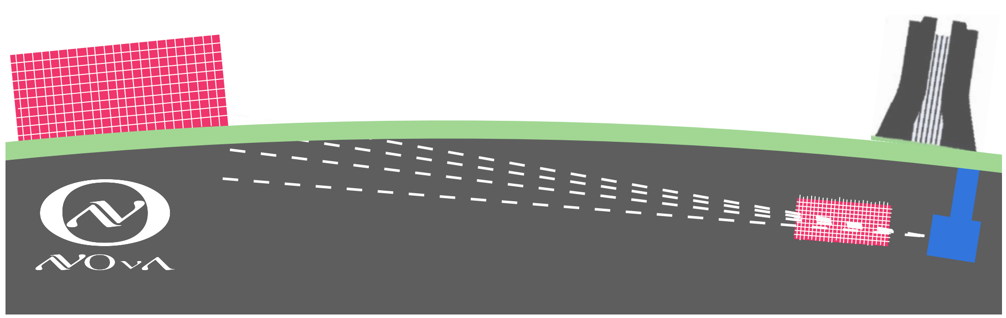
- NOvA has a broad physics program with different uncertainty treatment.
- NOvA uses most GENIE uncertainties provided.
- Special cases:
  - in-house ($|\vec{q}_3|$, q_0) **2p2h tune** to its ND data — and QE/RES-like uncertainties.
  - in-house **hN FSI tune** to external π-C scattering data — and uncertainties.
- Thanks to analysis design, interaction uncertainties are **controlled** for oscillation and cross section analyses.

Oscillation analysis

- **ND data-driven extrapolation reduces cross section uncertainties**.
- Uses 2p2h "QE/RES-like" uncertainty from ND data tune.

Cross section analysis

- **Analyses cannot use extrapolation**.
- Some cases opt for 2p2h model spread (Low E_{had}).



Future plans

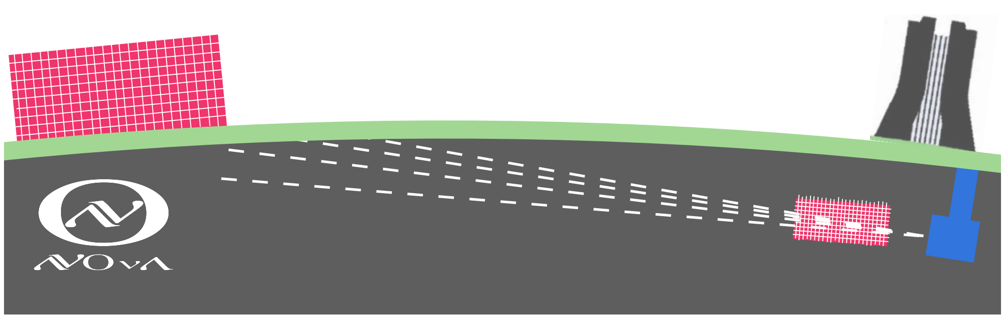
- NOvA still is actively seeking to improve its modeling and interaction uncertainties.
- Future synergy with DUNE anticipated, with aligned GENIE modeling choices.

Two Detectors

- **Have begun work on two-detector fits — a model driven approach.**
  - Have developed new degrees of freedom from these efforts.

Near Detector

- Efforts to address:
  - pion-related degrees of freedom.
  - resonance contributions.
- Continue to incorporate future 2p2h advancements from the community.

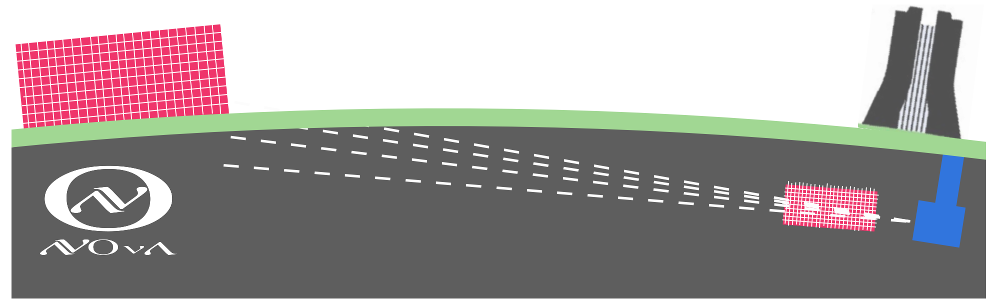


Thank you

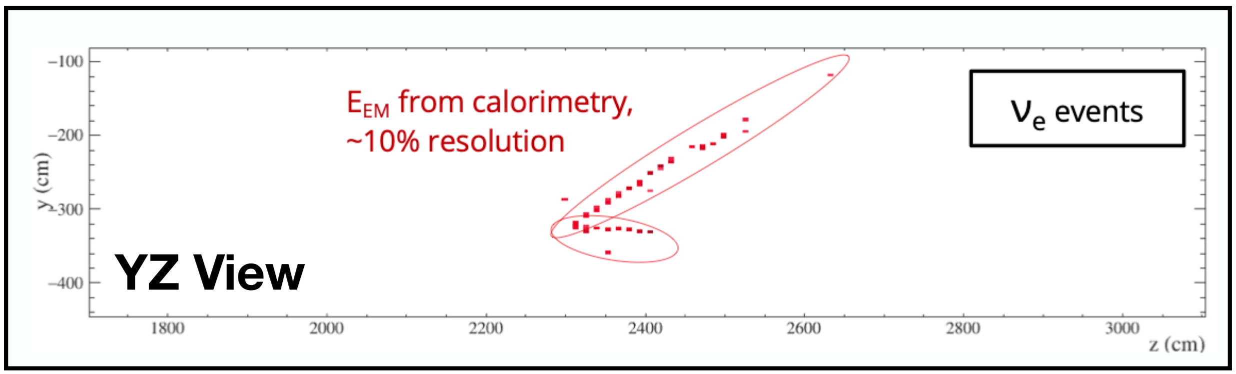
https://**nova**experiment.fnal.gov

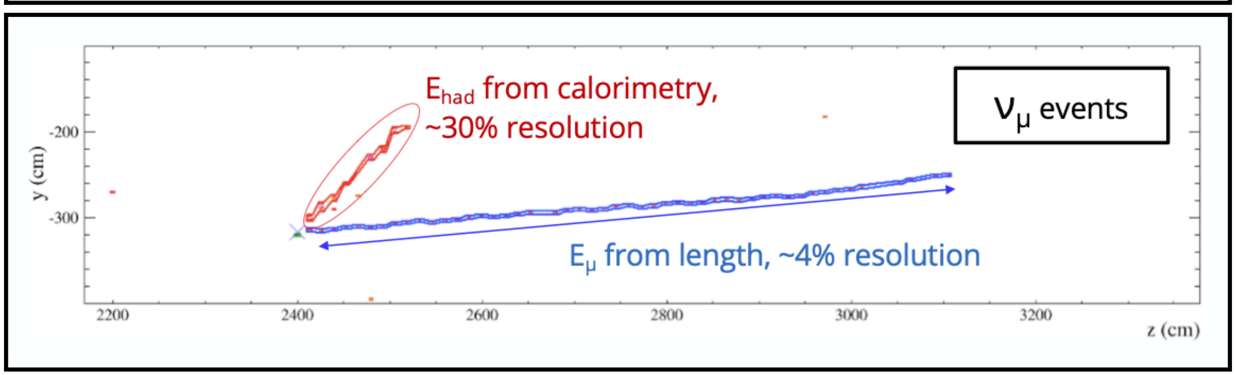
Backup

NOvA Experiment

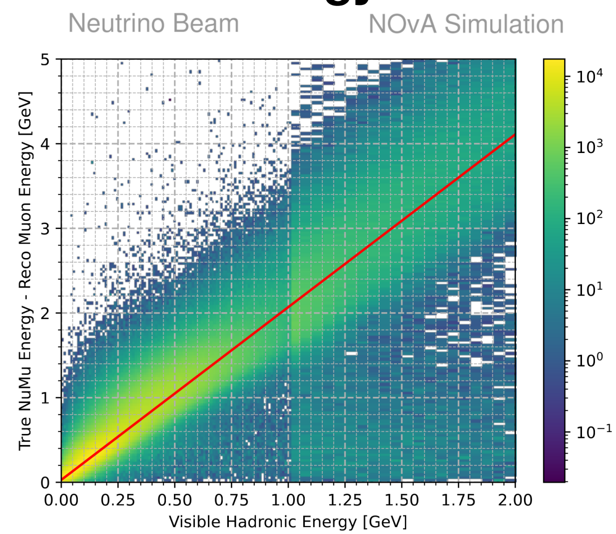


- Most analyses use a Convolutional Neural Network (CNN):
  - CNN for event ID — “3flavor”.
  - CNN for particle ID — cross sections.
  - CNN for hadronic vs. electromagnetic separation.

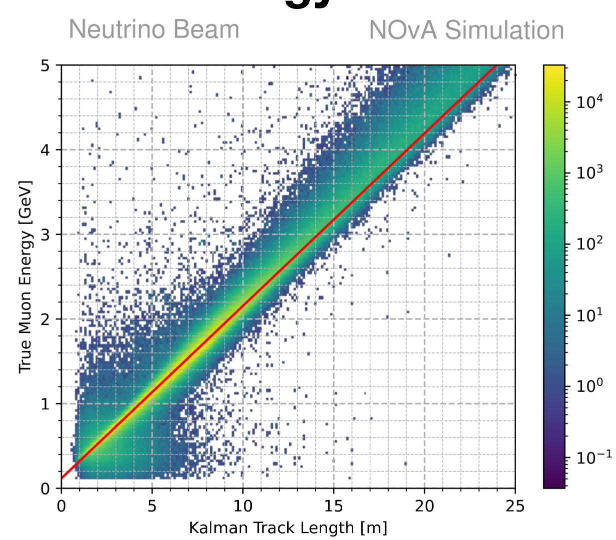




Hadronic Energy Resolution

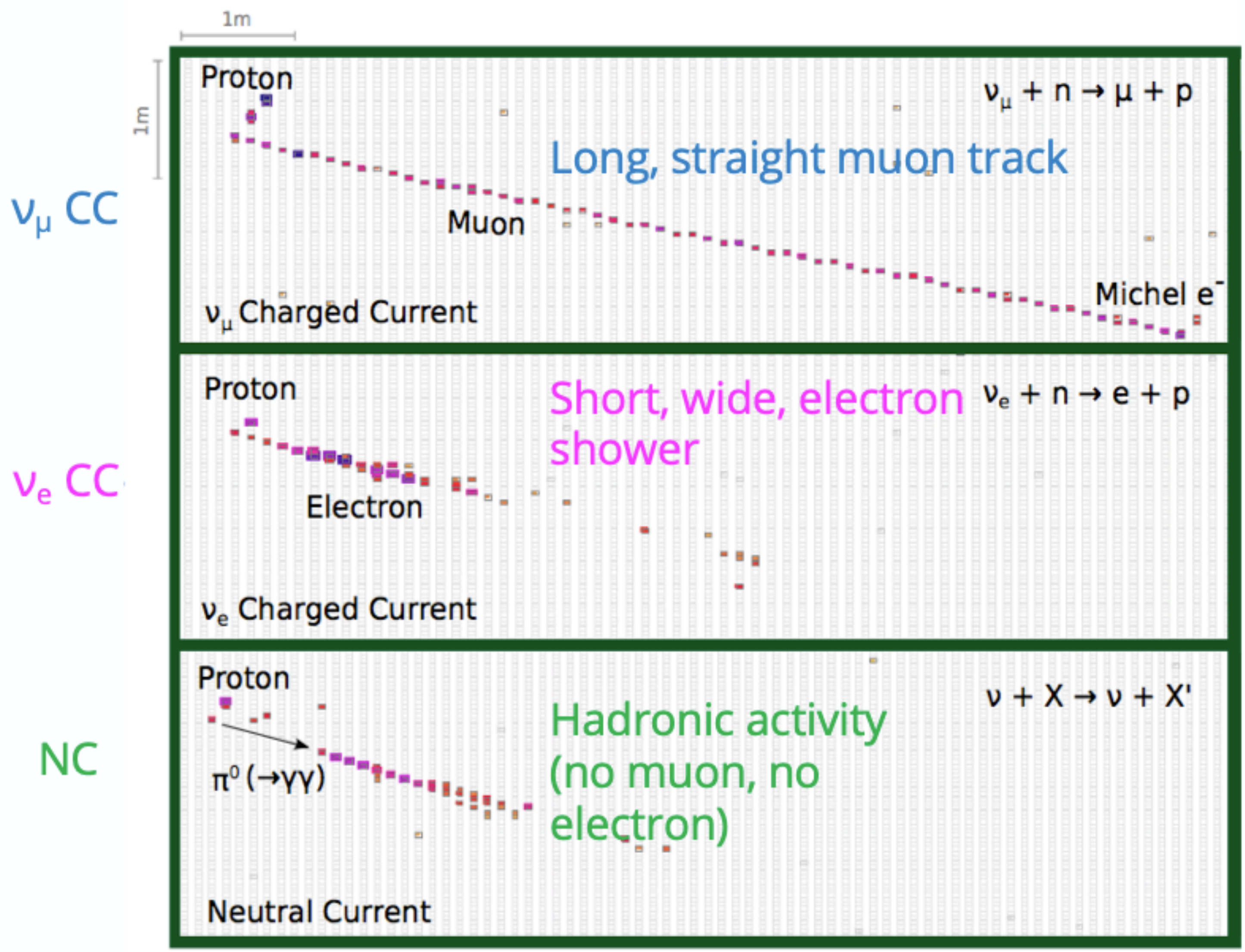


Muon Energy Resolution



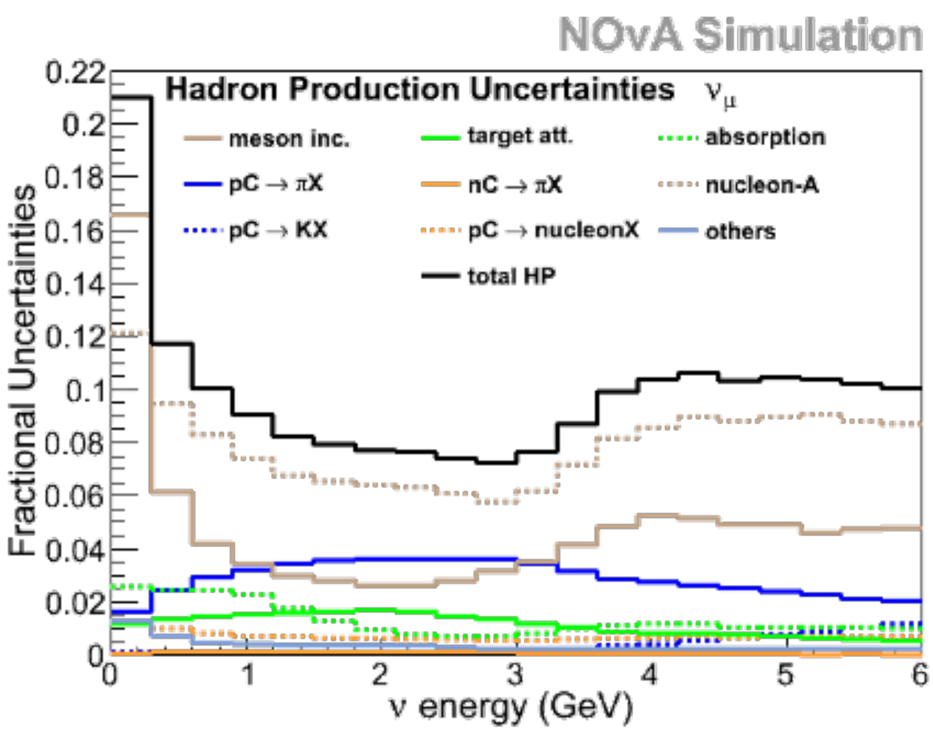
NOvA Experiment

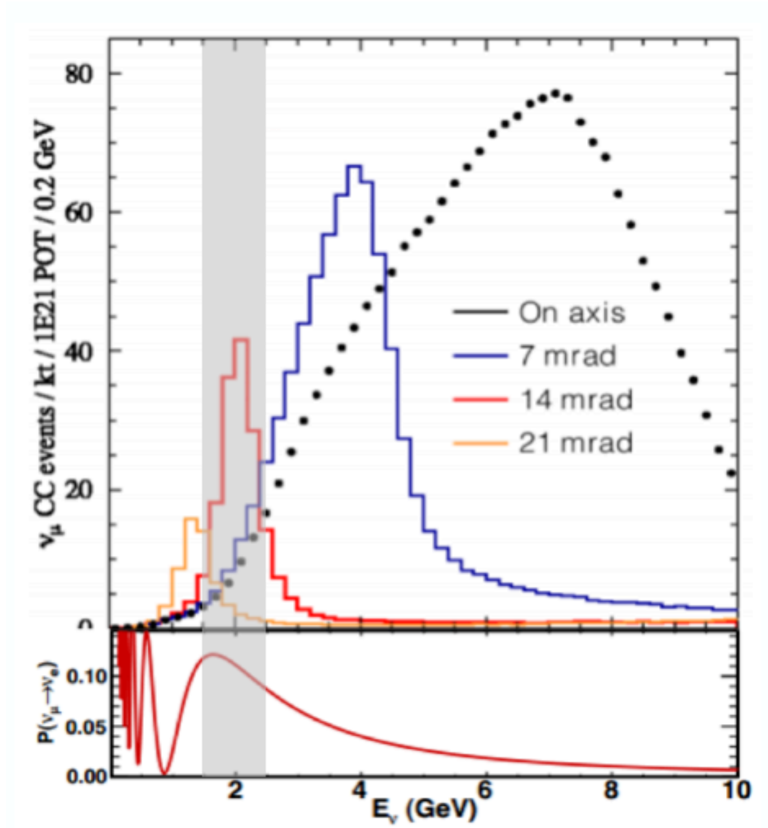
- Characteristics of events in NOvA detectors.



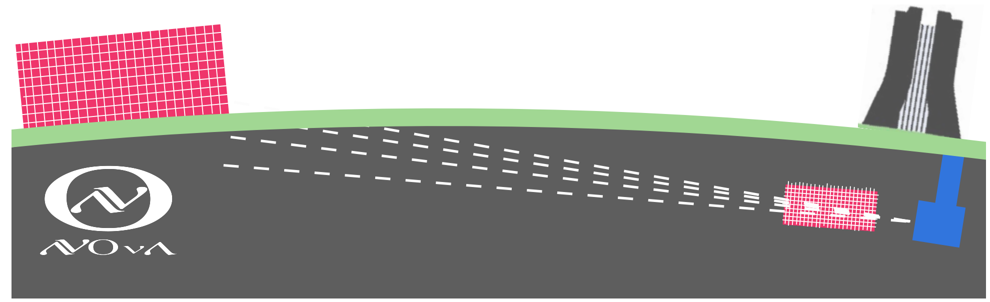
Flux Uncertainties

- Right, fractional uncertainty from hadronic analysis.
- Bottom, hadron production uncertainties, some of the leading uncertainties.

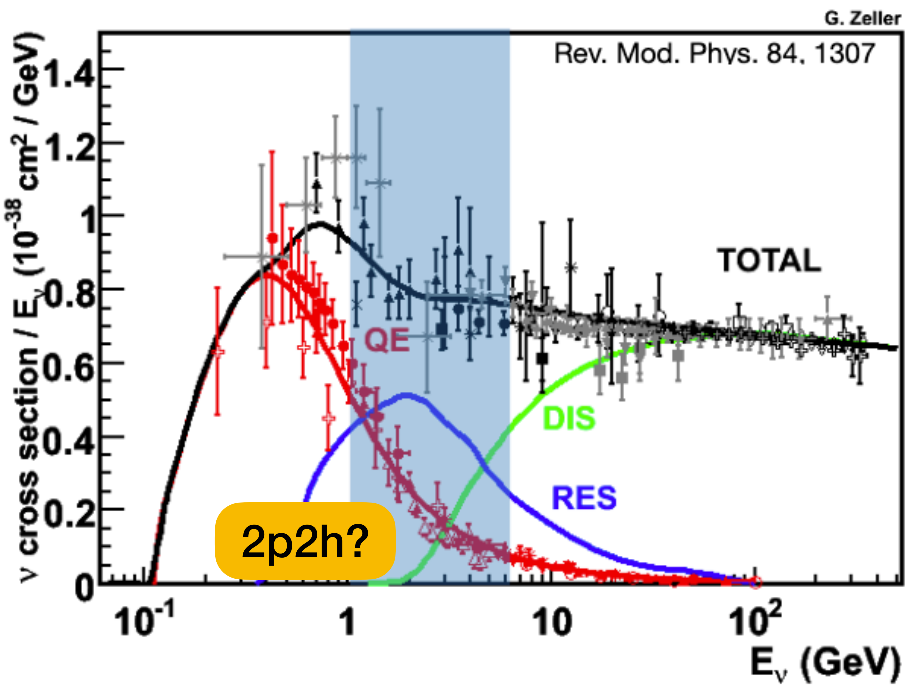


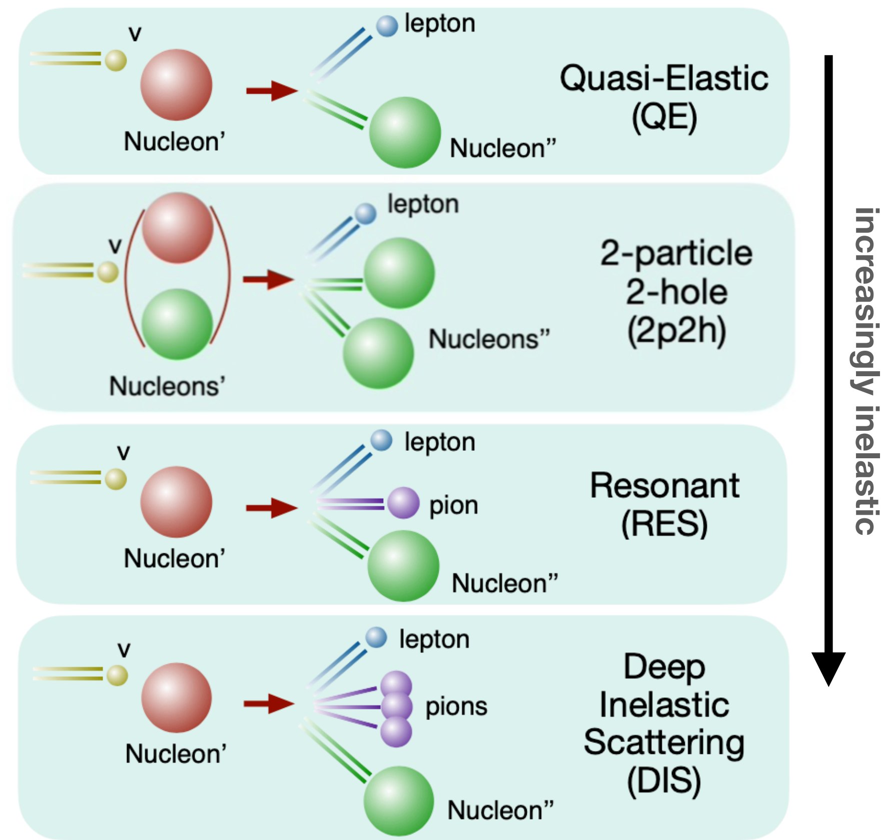


Interaction Model



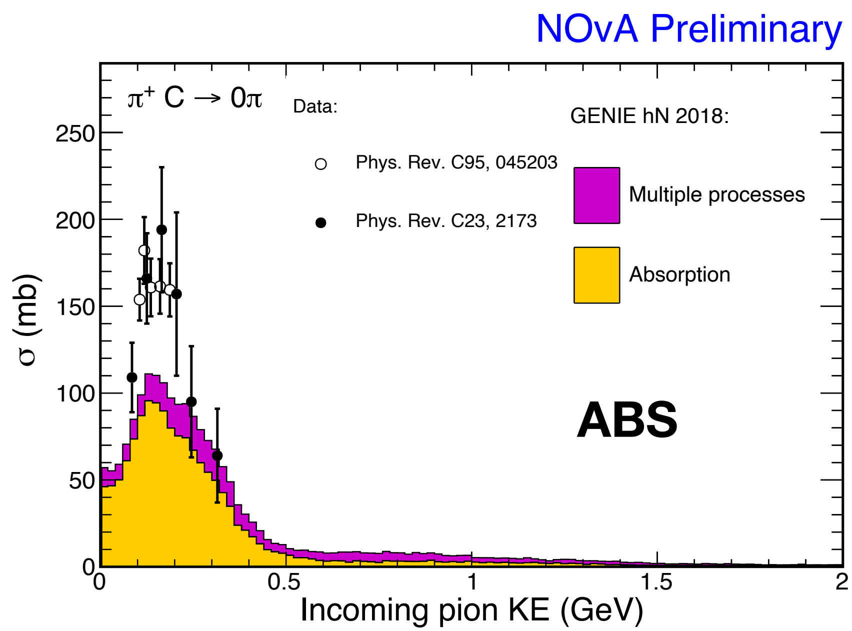
- Opportunity to study oscillation parameters (FD) **and** interactions from these processes (ND).

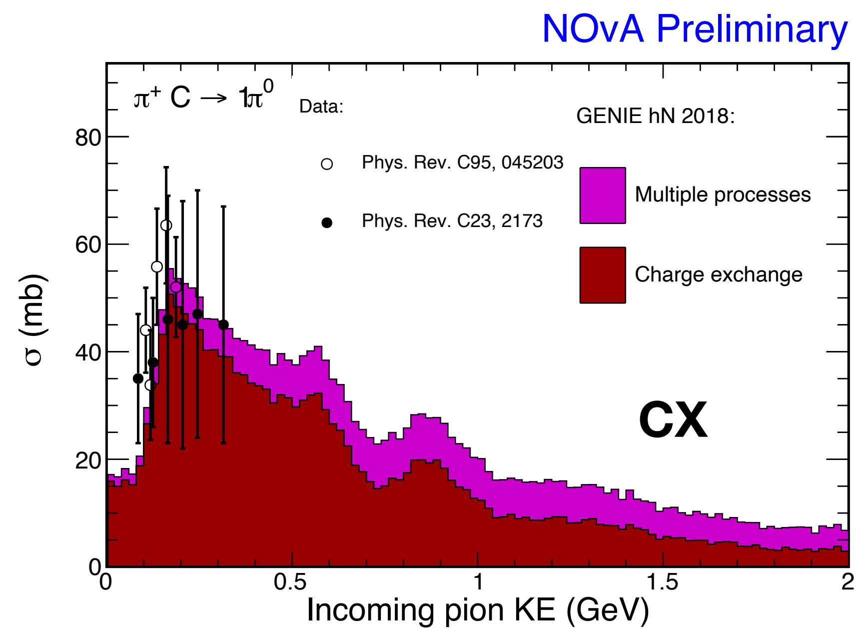


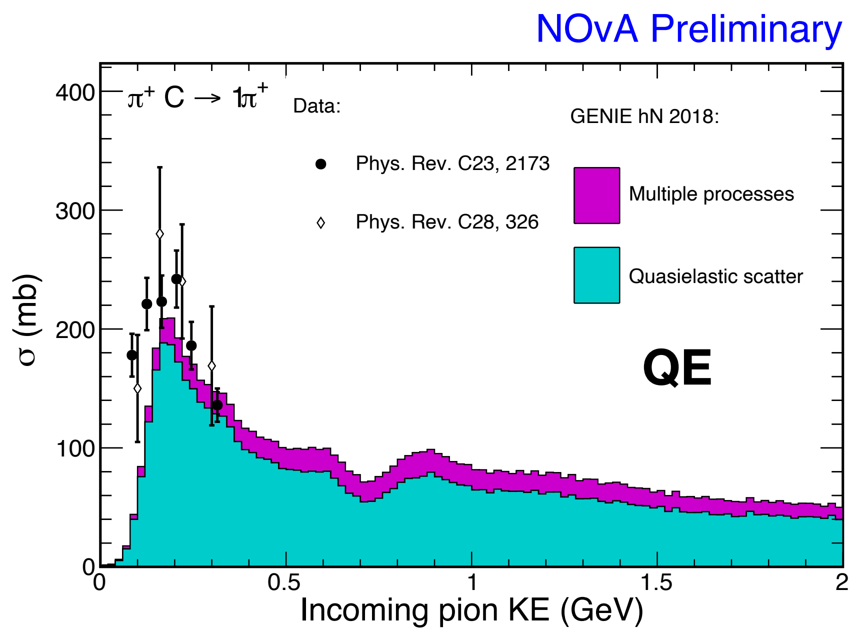


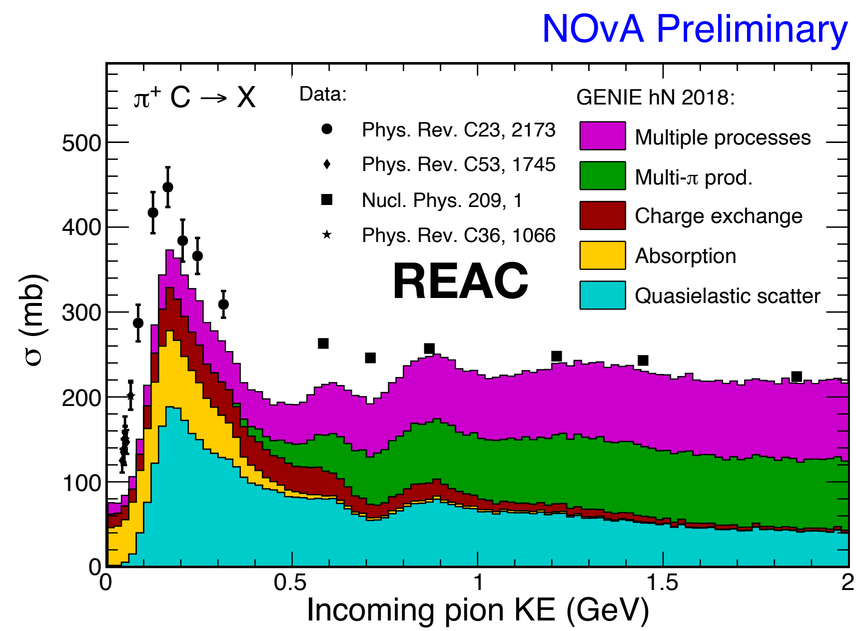
hN FSI and external data

GENIE 3.0.6









hN FSI tune

- Adjust the "fate fractions" of FSI processes.
- Tune to extant pion scattering data on C-12.
- Biggest change is to **Mean Free Path** and **Absorption**.

NOvA FSI Tune

MFP	Abs	CX	QE
0.6	1.4	0.7	0.9

Parameter	Scale factor name	Physics origin	Note
Mean free path (MFP)	f_{MFP}	$\rho(\vec{r})$, σ_{REAC}	The mean distance traveled by pions before they undergo an interaction.
Fraction of ABS	f_{ABS}	$\frac{\sigma_{ABS}}{\sigma_{\mathrm{REAC}}}$	The fraction of pion interactions experiencing an absorption.
Fraction of CX	f_{CX}	$\frac{\sigma_{CX}}{\sigma_{\mathrm{REAC}}}$	The fraction of pion interactions experiencing charge exchange.
Fraction of QE	f_{QE}	$\frac{\sigma_{QE}}{\sigma_{\mathrm{REAC}}}$	The fraction of pion interactions experiencing quasi-elastic scatters.

GENIE 3.0.6

* custom tuning

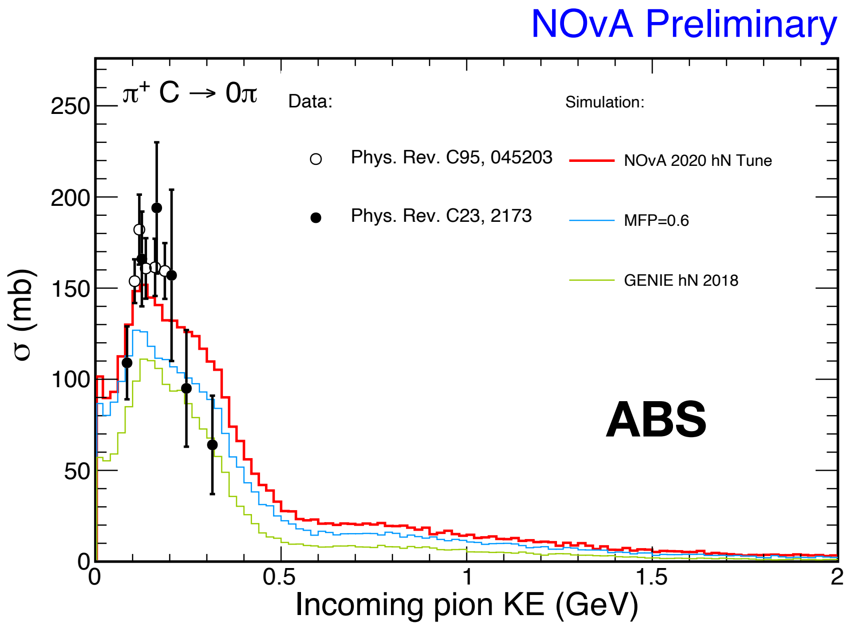
Process	Model	Reference
Final State Interactions	**hN semi-classical***	S. Dytman, Acta Physica Polonica B 40 (2009)

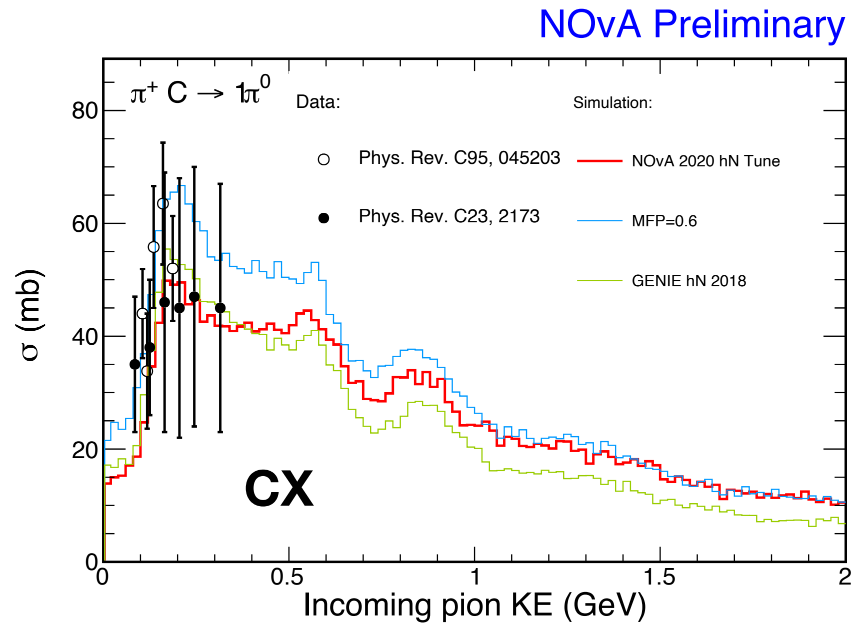
hN FSI tune

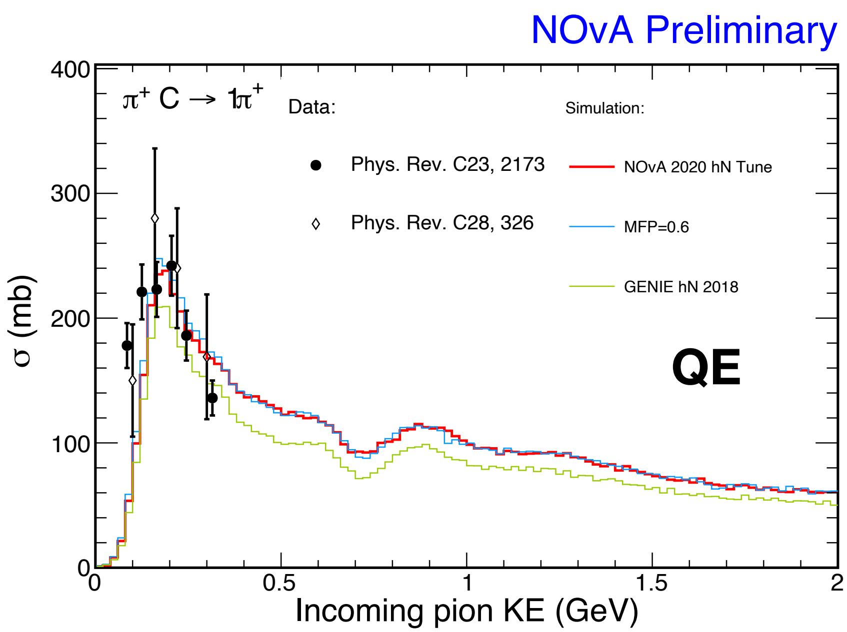
GENIE 3.0.6

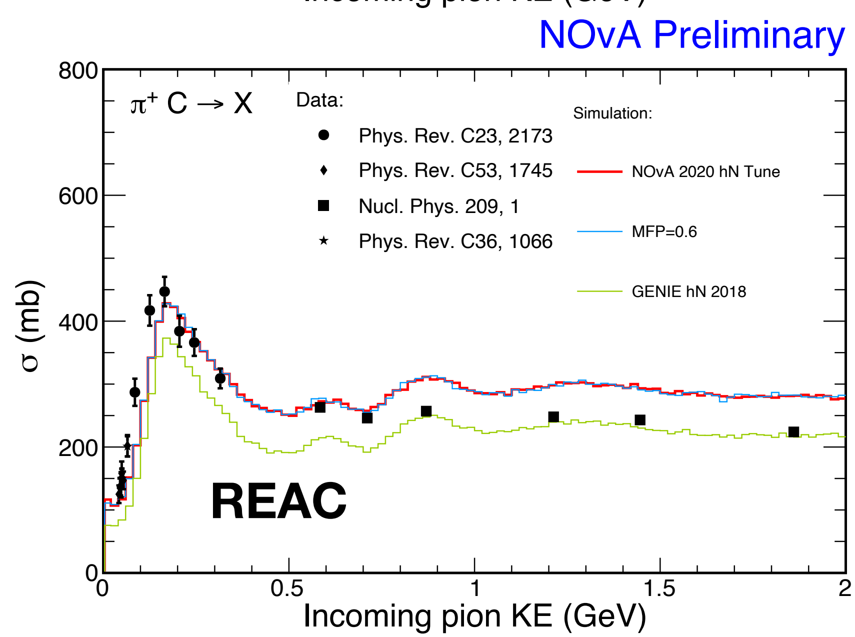
NOvA FSI Tune

MFP	Abs	CX	QE
0.6	1.4	0.7	0.9



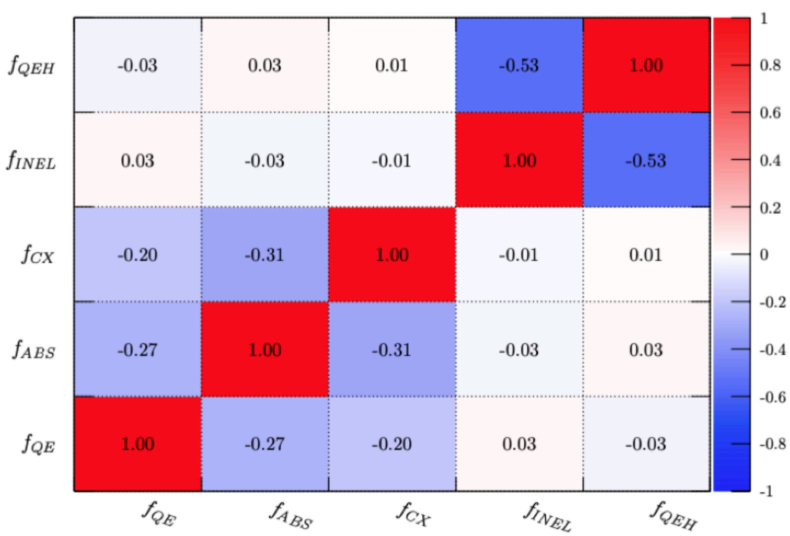






hN FSI uncertainty

- NOvA utilizes the covariance matrix from T2K, tuned on external data, to create uncertainties.
- Create a correlation matrix from their parameters, diagonalize the matrix, construct eigenvectors.
  - Use bottom left 3x3 block.
- Produce three eigenvalue/eigenvector linear combinations of the FSI processes.
- Fourth uncertainty of ±0.2 adjustment of MFP.



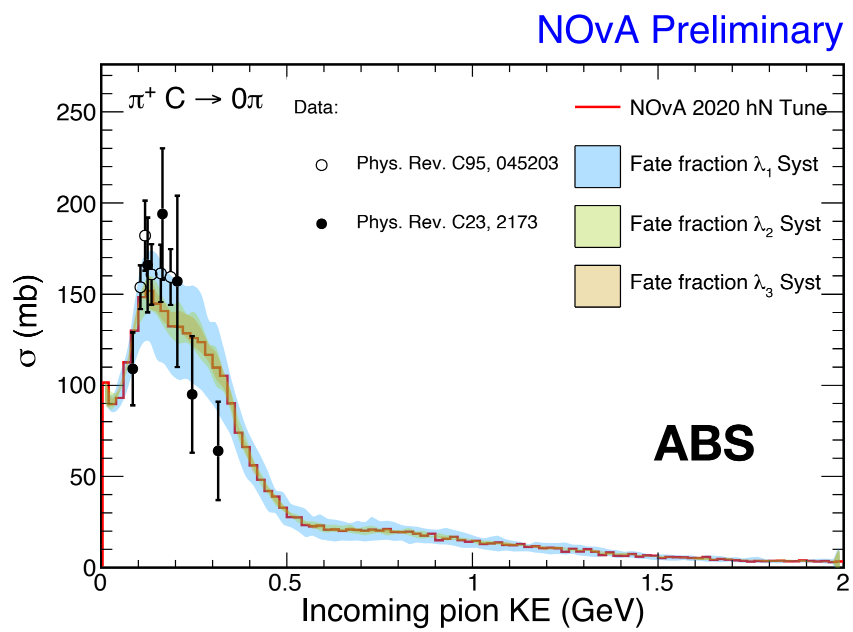
[7] E. S. Pinzon Guerra et al. Using world charged $\pi^{\pm}$−nucleus scattering data to constrain an intranuclear cascade model. *Phys. Rev.*, D99(5):052007, 2019.

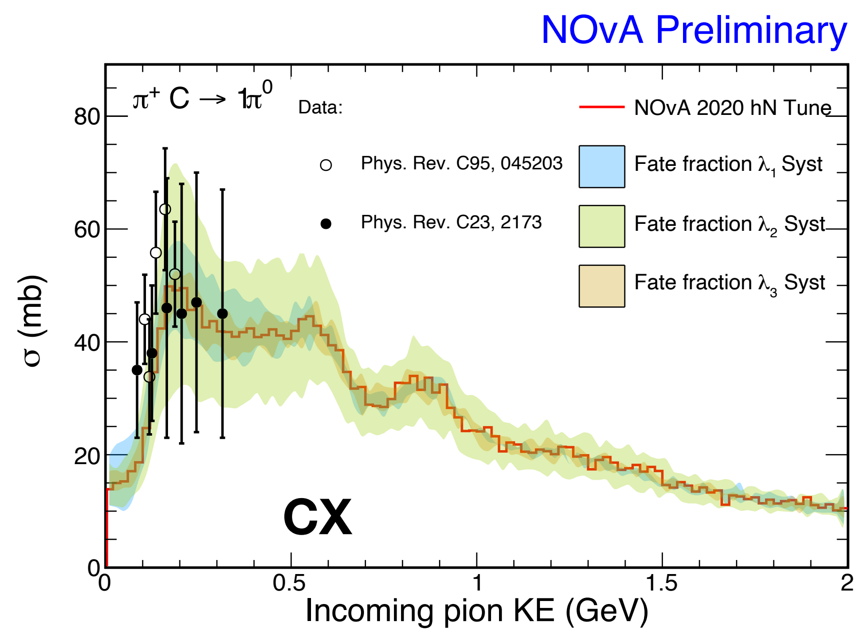
NOvA's FSI Uncertainties

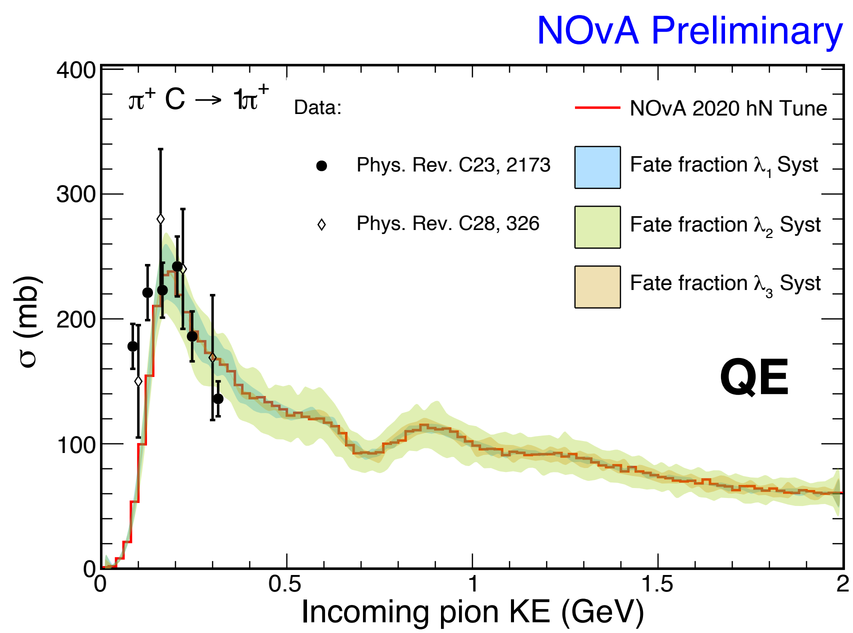
$$\begin{bmatrix} f^1_{\mathrm{ABS}} \\ f^1_{\mathrm{CX}} \\ f^1_{\mathrm{QE}} \end{bmatrix} = \sqrt{\lambda_1}\vec{v}_1$$

Knob	shift (σ)	f_{MFP}	f_{ABS}	f_{CX}	f_{QE}
Fate fraction #1	+1	0.6	0.9	0.8	1.0
	-1	0.6	1.8	0.6	0.8
Fate fraction #2	+1	0.6	1.4	0.9	0.7
	-1	0.6	1.4	0.5	1.2
Fate fraction #3	+1	0.6	1.3	0.5	0.8
	-1	0.6	1.4	0.9	1.0
Mean free path	+1	0.8	1.4	0.7	0.9
	-1	0.4	1.4	0.7	0.9

hN FSI uncertainty



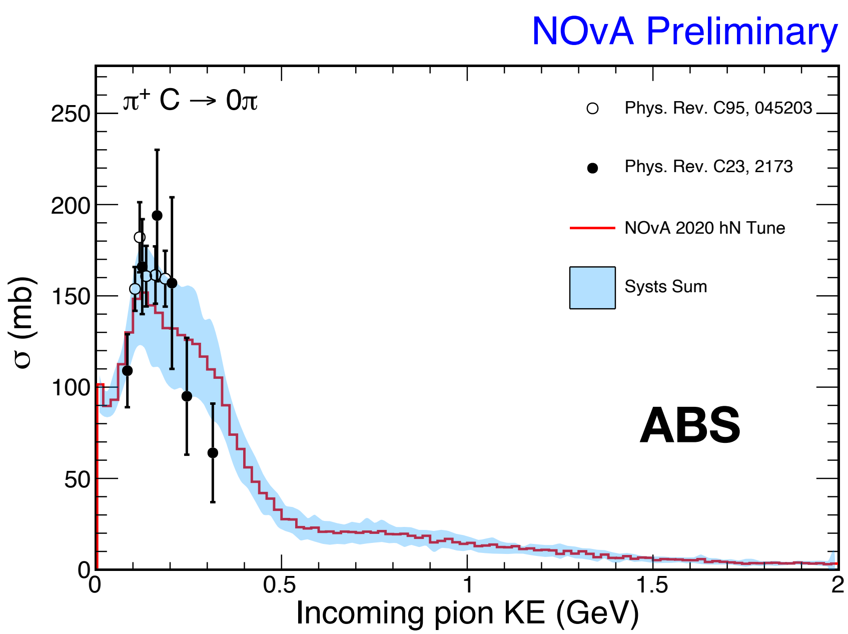


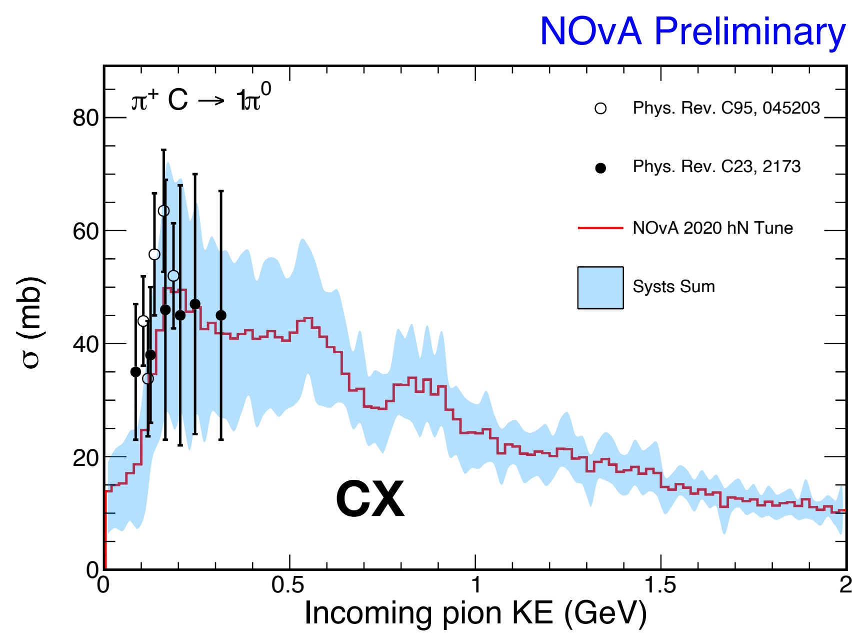


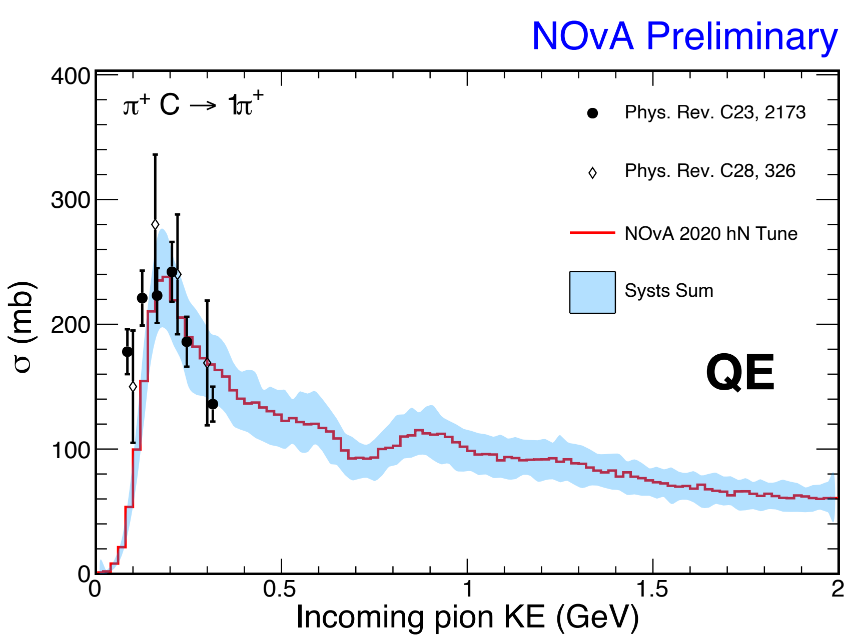
Knob	shift (σ)	f_{MFP}	f_{ABS}	f_{CX}	f_{QE}
Fate fraction #1	+1	0.6	0.9	0.8	1.0
	-1	0.6	1.8	0.6	0.8
Fate fraction #2	+1	0.6	1.4	0.9	0.7
	-1	0.6	1.4	0.5	1.2
Fate fraction #3	+1	0.6	1.3	0.5	0.8
	-1	0.6	1.4	0.9	1.0
Mean free path	+1	0.8	1.4	0.7	0.9
	-1	0.4	1.4	0.7	0.9

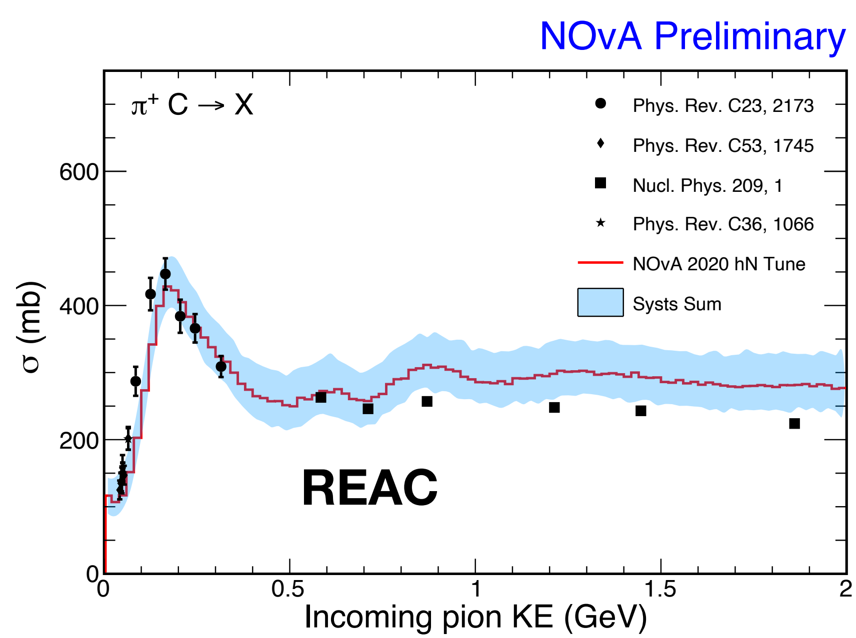
hN FSI uncertainty

total systematic uncertainty



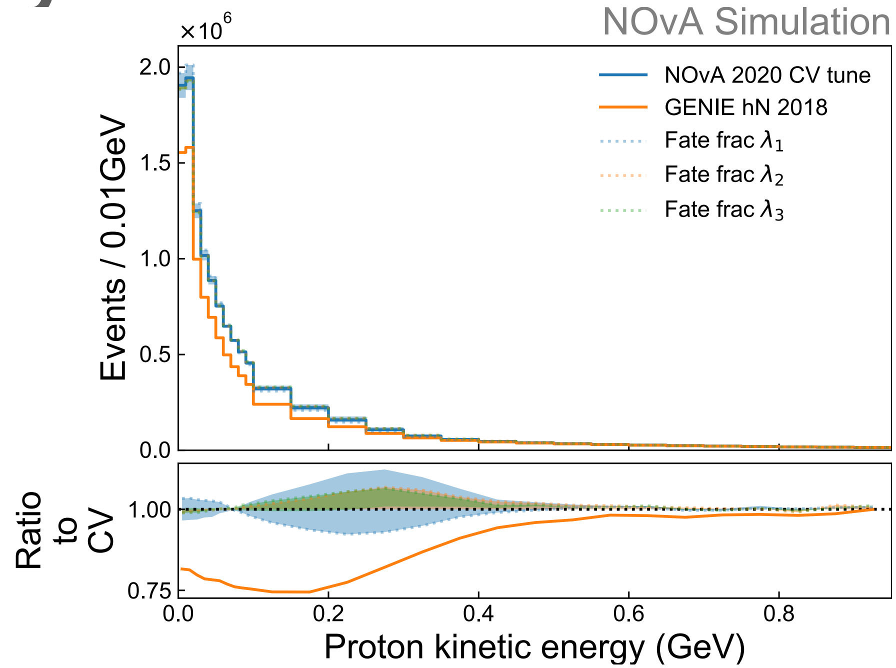


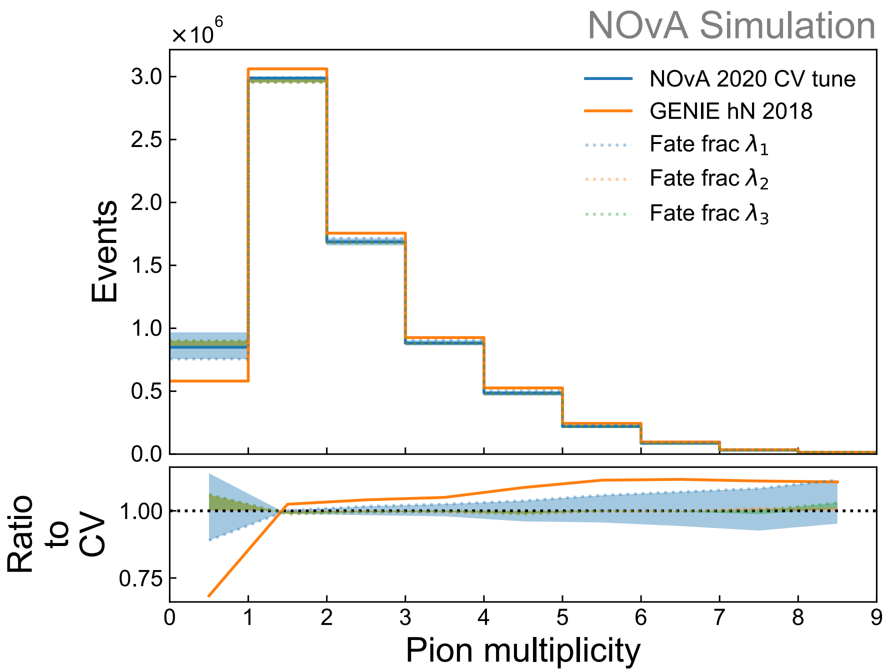


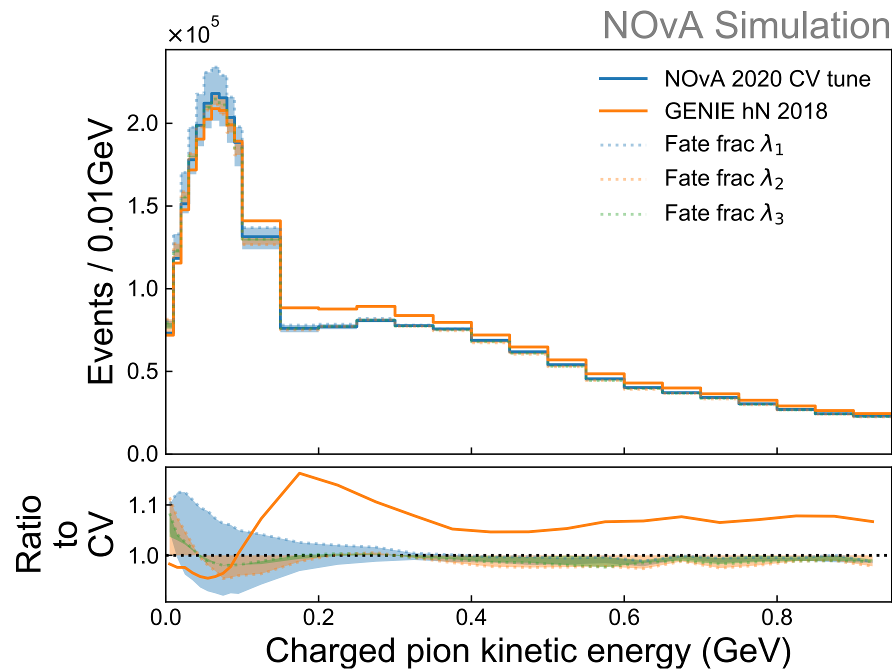


hN FSI uncertainty

- Impact on neutrino oscillation-related observables.
- Largest impact is in ~ 200 MeV range.
- MFP uncertainty is a leading uncertainty in oscillation analysis.







NOvA Oscillations

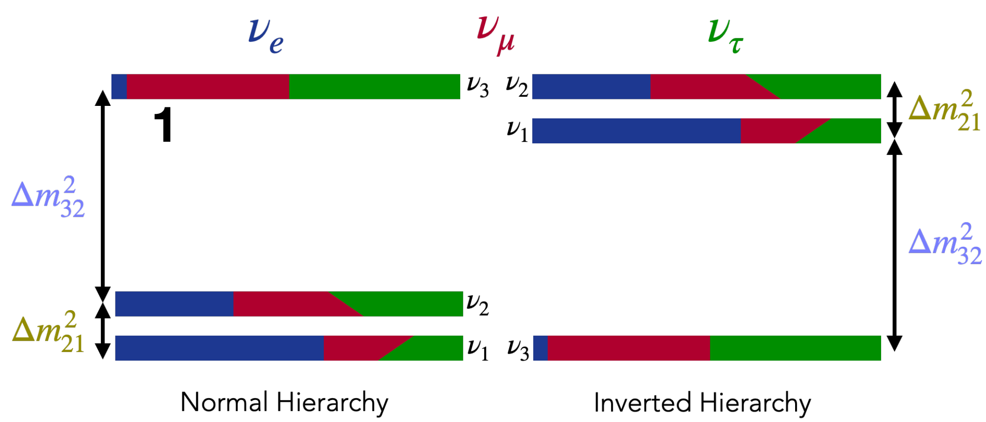
- Three main questions:

3

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

2

$c_{ij} \rightarrow \cos(\theta_{ij})$
$s_{ij} \rightarrow \sin(\theta_{ij})$



Appearance Probability

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \sin 2\theta_{13} \frac{\sin^2 \Delta(1-A)}{(1-A)^2} + \alpha J \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{(1-A)}$$

Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) + \mathcal{O}(\alpha, \sin^2\theta_{13})$$

$$\Delta \equiv \Delta m^2_{13} L / 4E_\nu$$

$$\Delta m^2_{32} = m^2_3 - m^2_2$$

1

- **mass ordering** of eigenstates?
- Sensitive to Disappearance, P($\nu_\mu \rightarrow \nu_\mu$): θ_{23} and Δm^2_{32}.

2

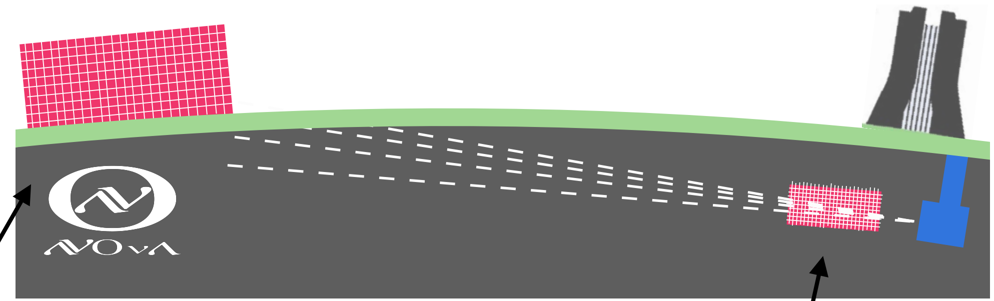
- **value of** θ_{23} — an underlying symmetry of ν_μ and ν_τ?

3

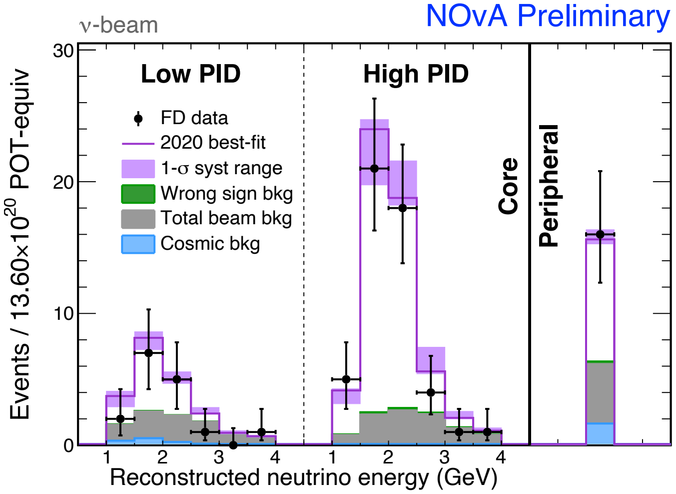
- δ_{CP} , matter vs. antimatter asymmetry in lepton sector?

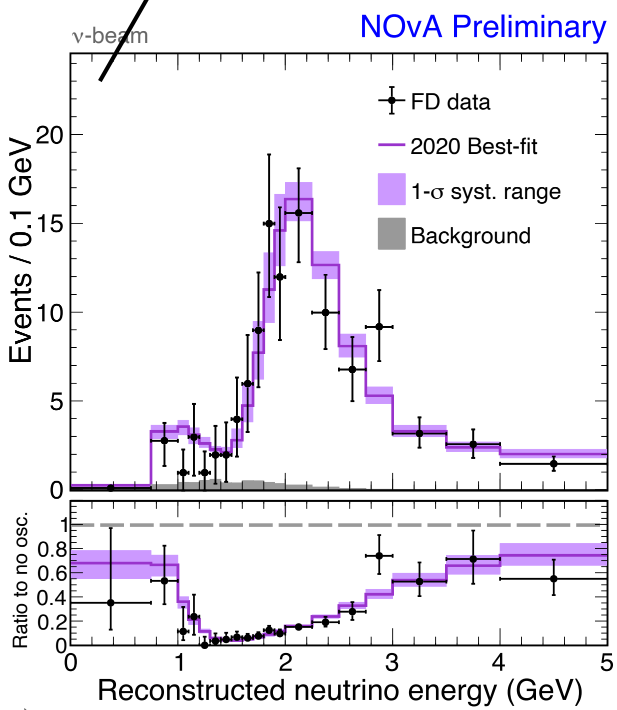
NOvA Oscillations

- From Neutrino 2020 analysis:
  - 211 (105) ν_μ $(\bar{\nu}_\mu)$ events.
  - 82 (33) ν_e $(\bar{\nu}_e)$ events.

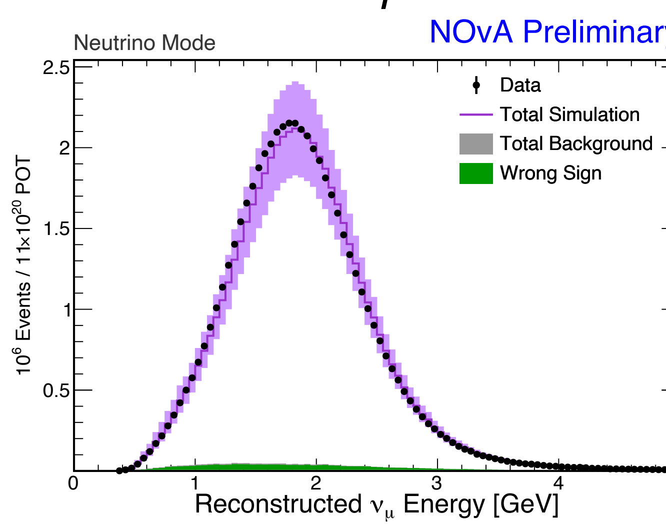


FD Spectra





ND Spectrum



Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right) + \mathcal{O}(\alpha, \sin^2\theta_{13})$$

$$\Delta \equiv \Delta m^2_{13}L/4E_\nu$$

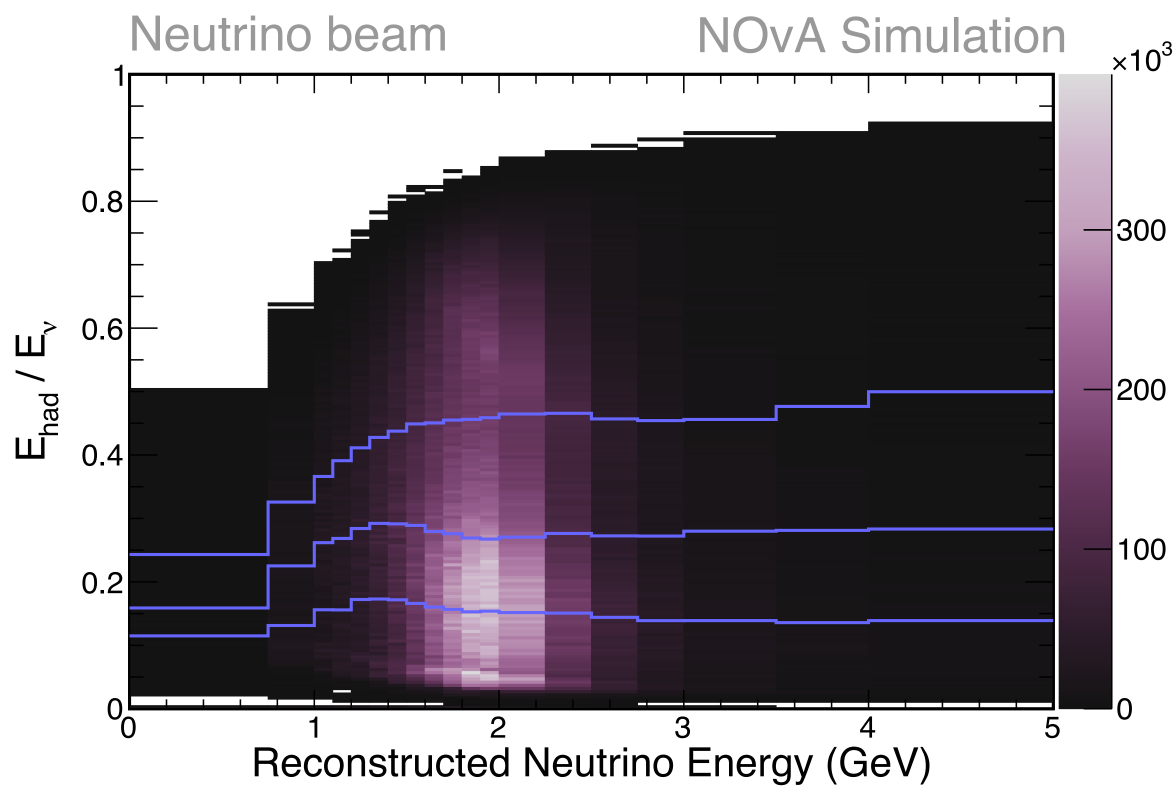
$$\Delta m^2_{32} = m^2_3 - m^2_2$$

Appearance Probability

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha J\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)}$$

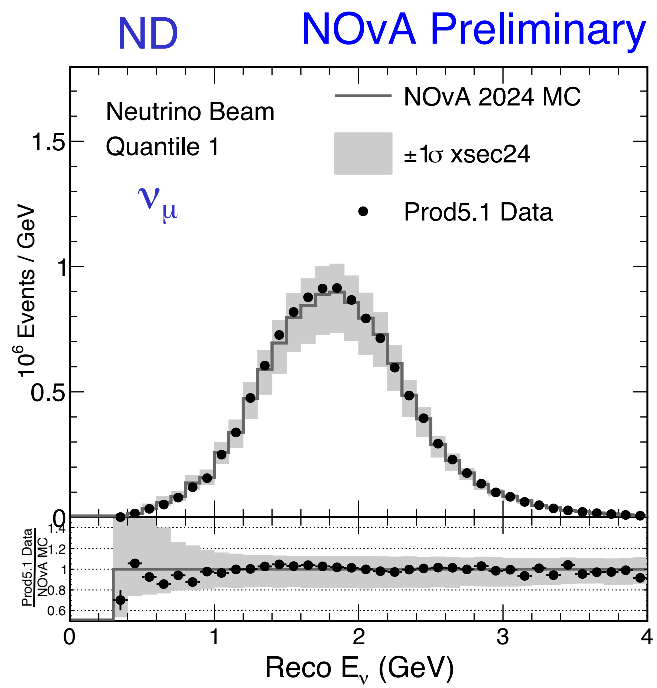
ND Quantile distributions

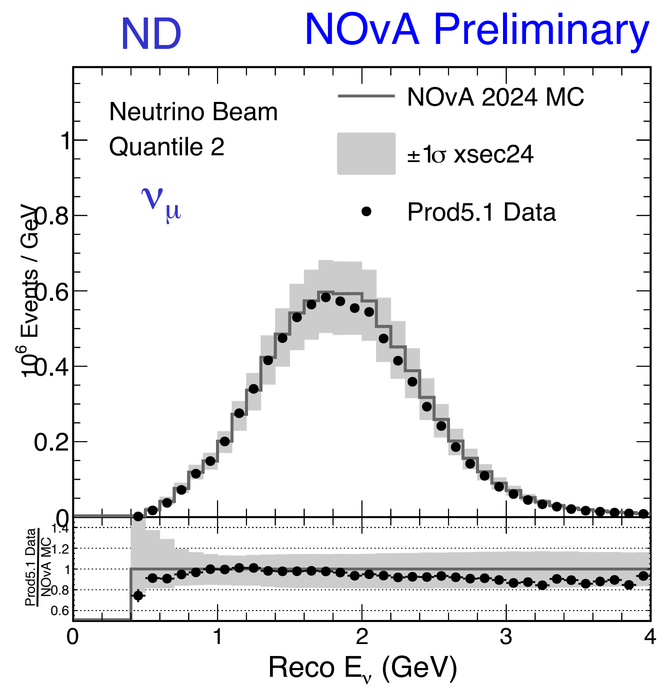
- In Near Detector, we divide the ν_μ distributions into 4 quartiles based on hadronic energy contribution.

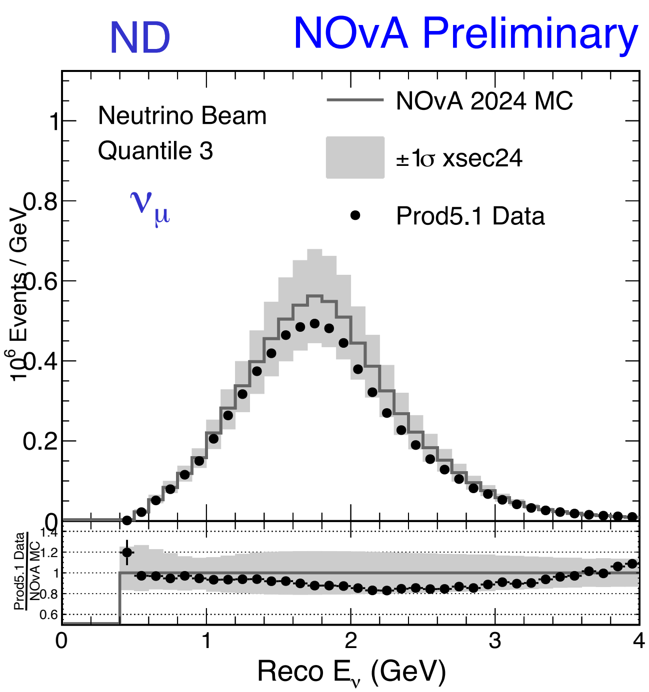


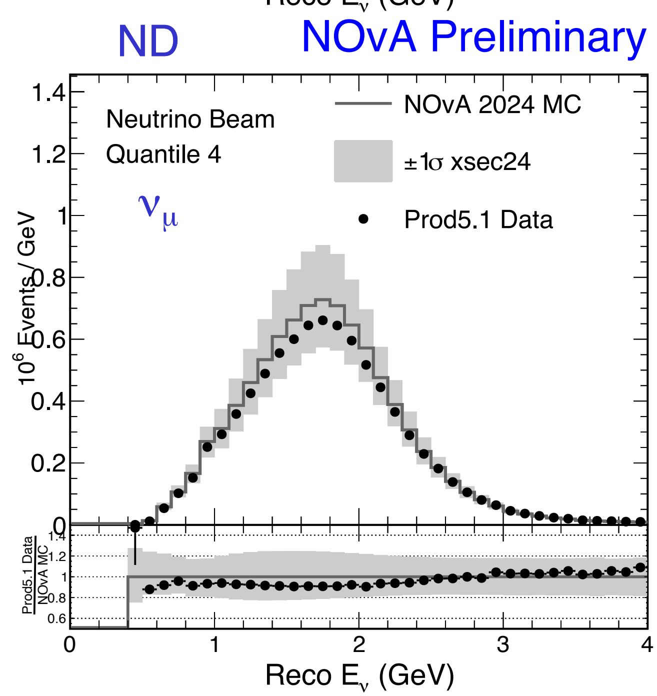
Cross section uncertainty in ND

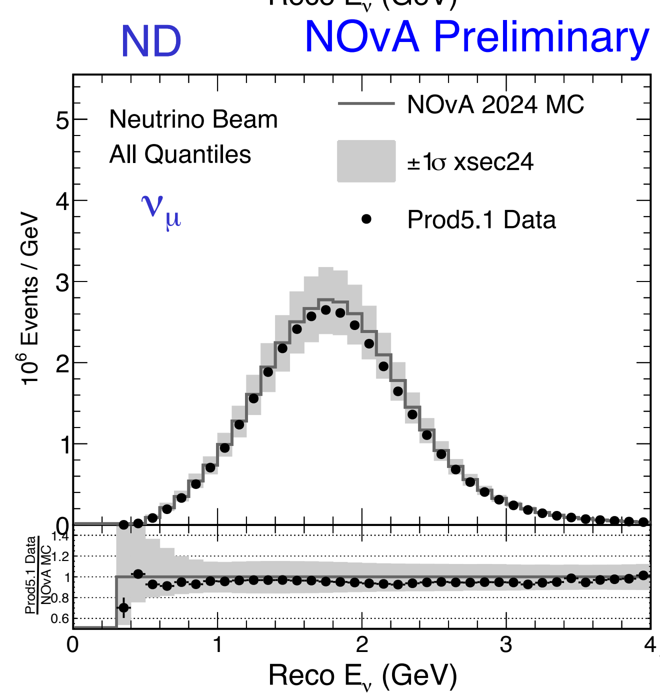
- $\pm 1\sigma$ error budget of NOvA's cross section uncertainties in Near Detector.





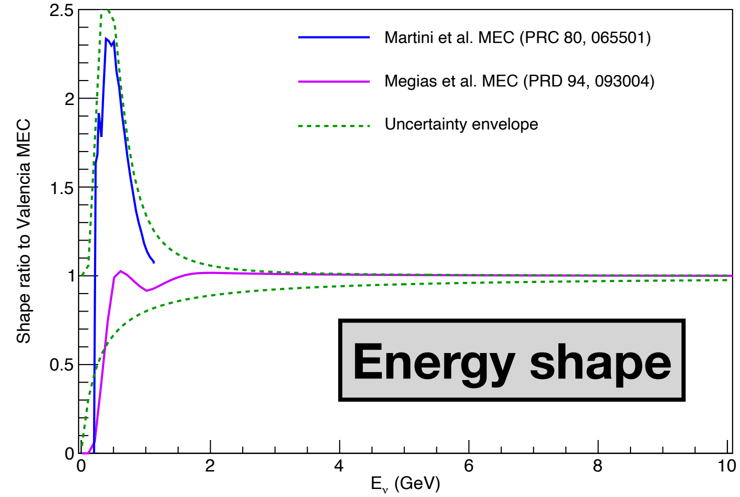


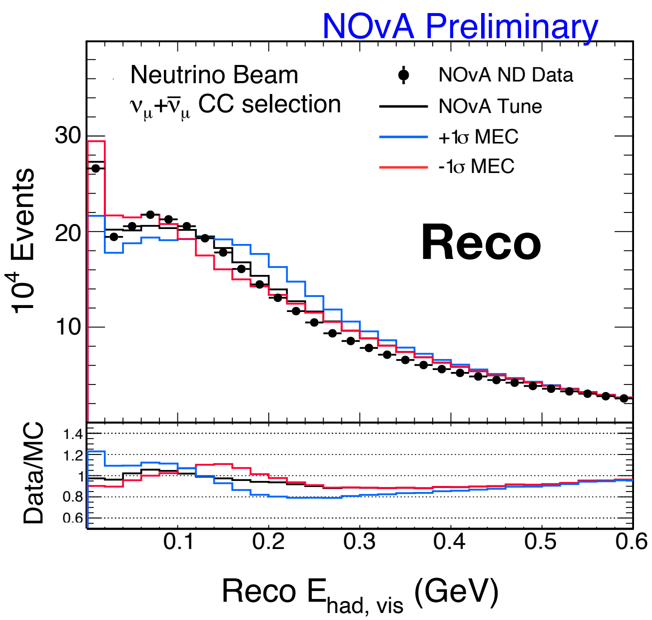




2p2h Uncertainty in NOvA

Systematic	QE-like	RES-like
Z-expansion CCQE	1	-1
Z-expansion coefficients	1	-1
CCQE RPA suppression	1	-1
CCQE RPA enhancement	1	-1
RES M_V	-1	1
RES M_A	-1	1
RES low-Q^2 suppression:	1	-1

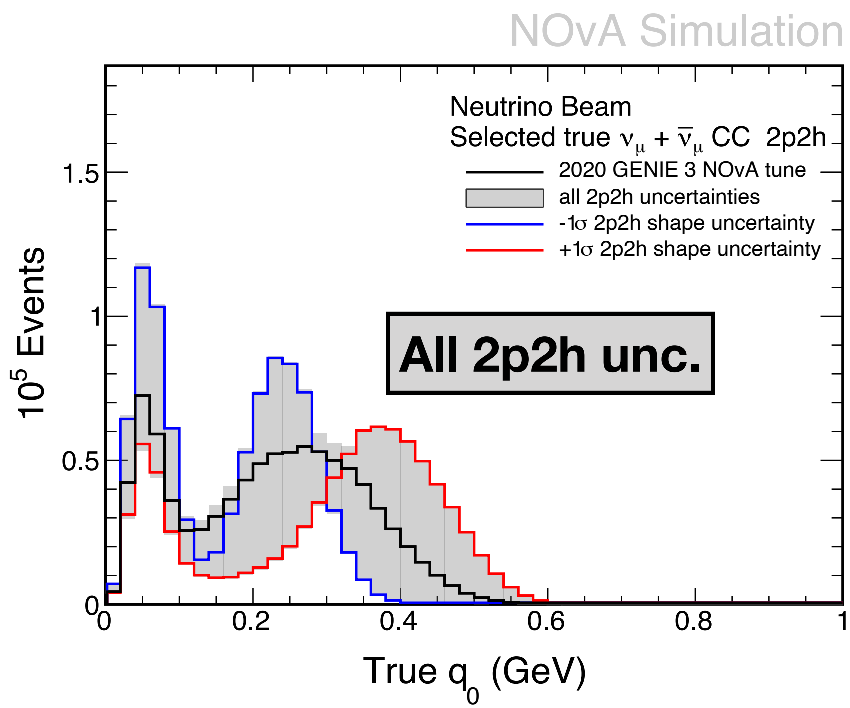




np/nn fraction

$$\frac{np}{np+pp} = 0.66 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

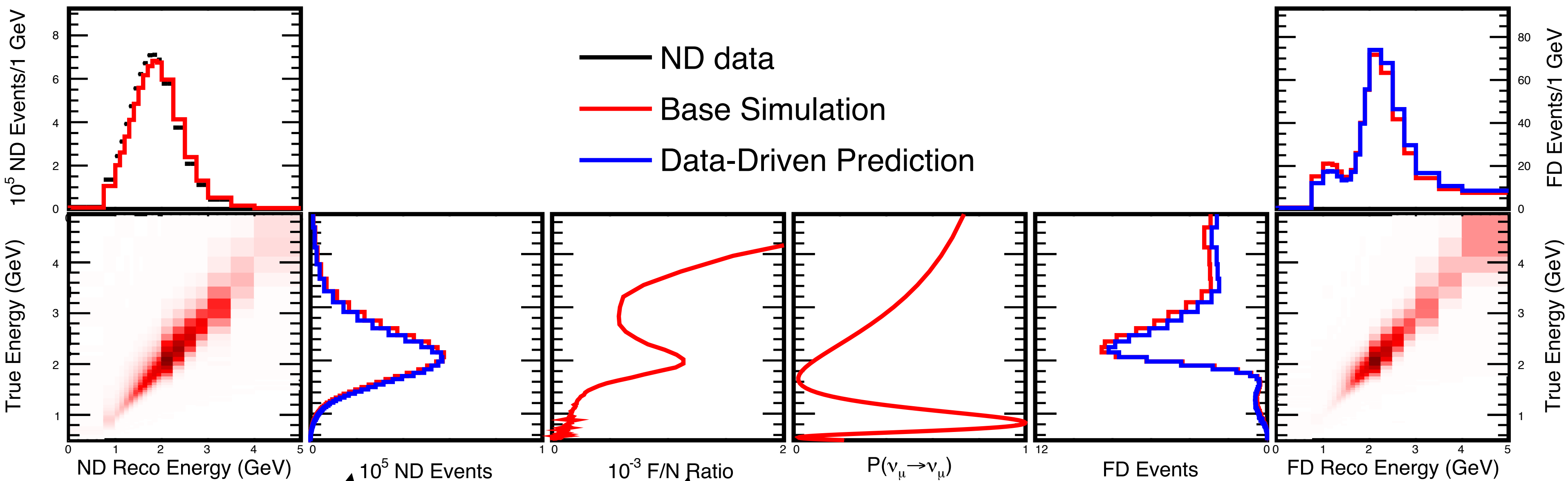
$$\frac{np}{np+nn} = 0.69 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$



Extrapolation

- Our FD prediction is more than just a "simple prediction.
- Includes several important components…

$$\tilde{N}^{j}_{FD}{}' = \left\{ \left[\sum_i \left(\frac{F}{N}\right)_i R^{ij}_{FD} R^{-1\,ij}_{ND} P^i \right] \tilde{N}^{j}_{ND}{}' \right\} = \left\{ \tilde{N}^{j\,MC}_{FD} \right\} \frac{\tilde{N}^{j\,data}_{ND}}{\tilde{N}^{j\,MC}_{ND}}$$



Reco. smearing

ND data-driven correction to prediction

Detector differences (e.g. acceptance)

Oscillate the prediction

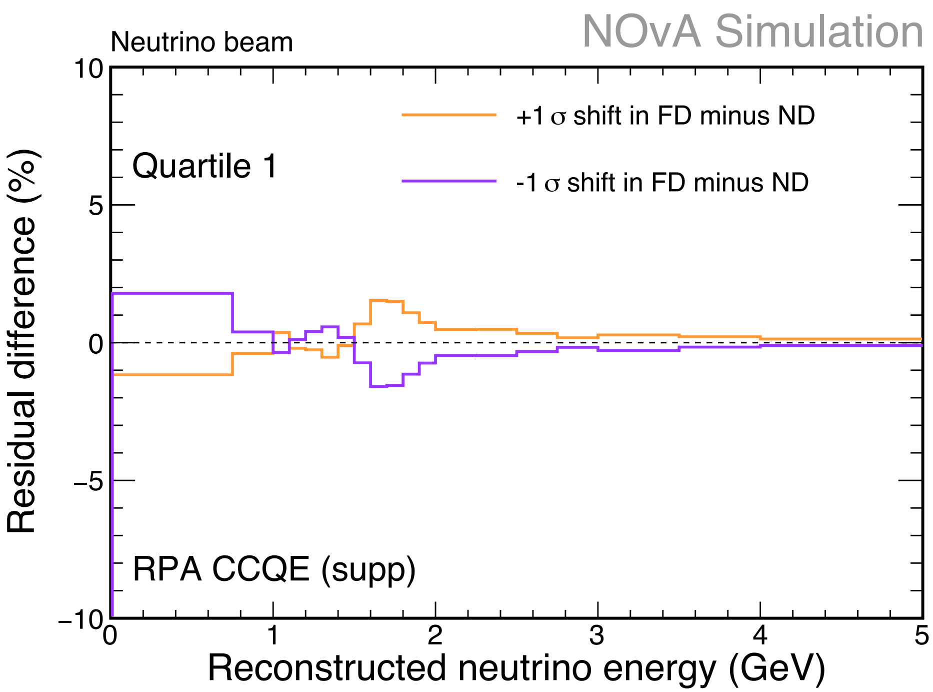
ND data-driven FD pred

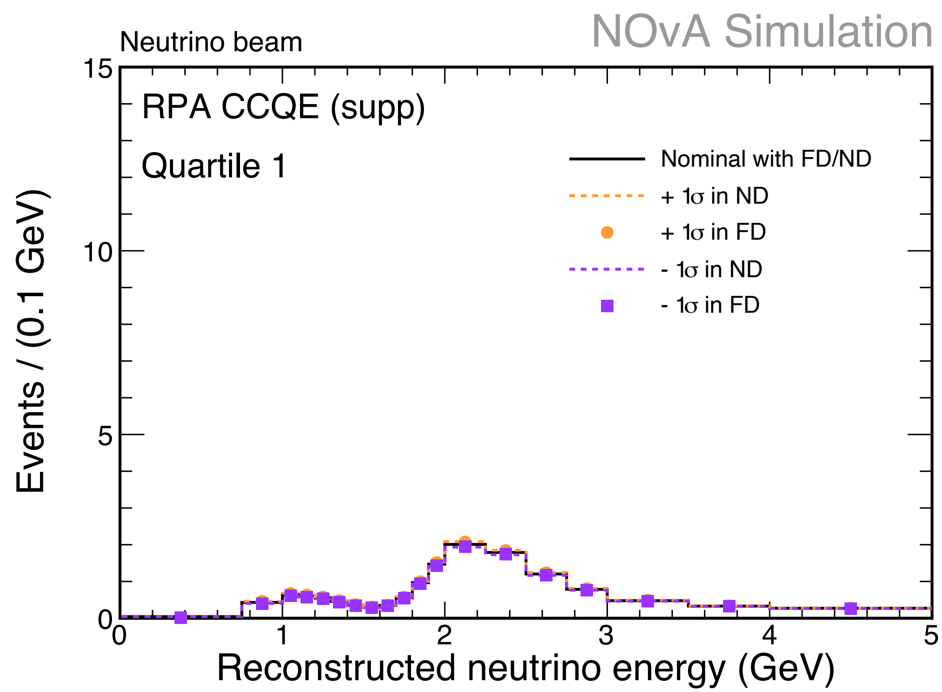
Reco. smearing

Extrapolation

- Left, our remaining uncertainty after extrapolated ND prediction.
- Right, different FD predictions, extrapolated and un-extrapolated.

$$\widetilde{N^j_{FD}}' = \left\{ \left[\sum_i \left(\frac{F}{N}\right)_i R^{ij}_{FD} R^{-1ij}_{ND} P^i \right] \widetilde{N^j_{ND}}' \right\} = \left\{ \widetilde{N^{j\,MC}_{FD}} \right\} \frac{\widetilde{N^{j\,data}_{ND}}}{\widetilde{N^{j\,MC}_{ND}}}$$





Extrapolation

$$\widetilde{N^j_{FD}}' = \left\{ \left[\sum_i \left(\frac{F}{N} \right)_i R^{ij}_{FD} R^{-1\,ij}_{ND} P^i \right] \widetilde{N^j_{ND}}' \right\} = \left\{ \widetilde{N^{j\,MC}_{FD}} \right\} \frac{\widetilde{N^{j\,data}_{ND}}}{\widetilde{N^{j\,MC}_{ND}}}$$

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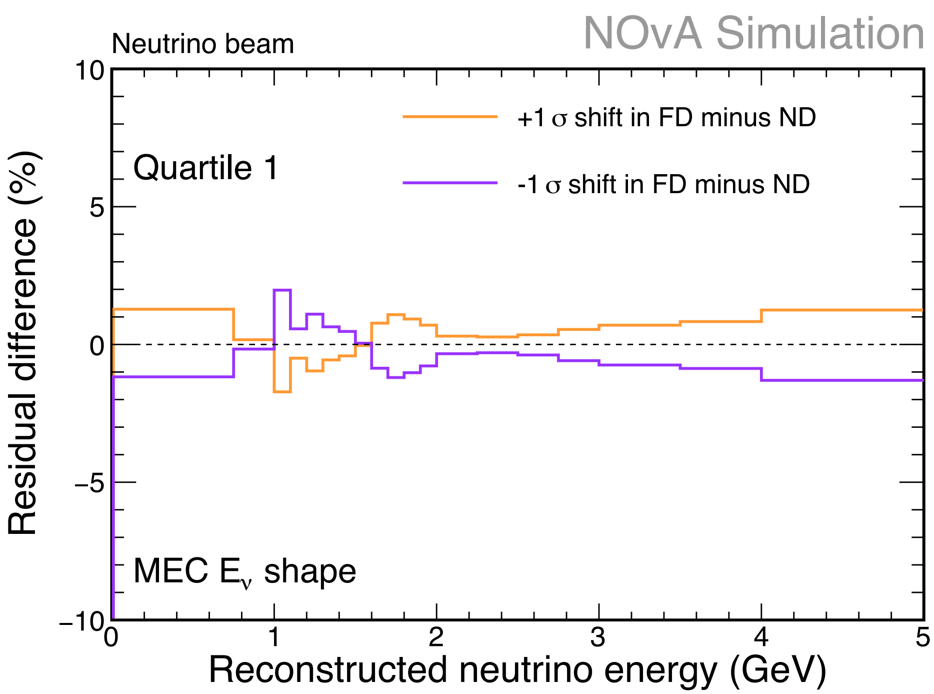
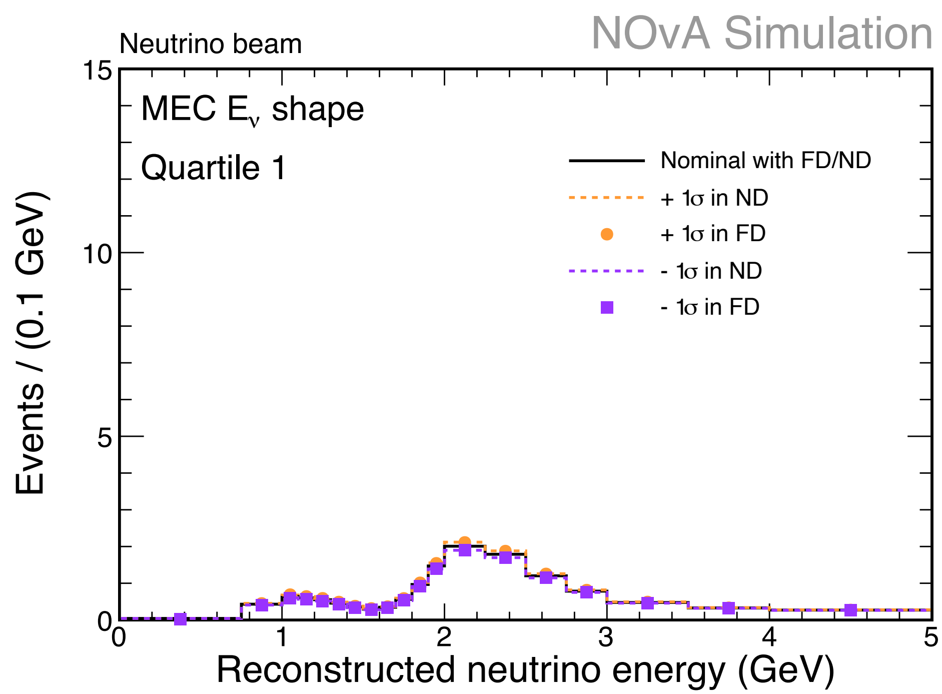
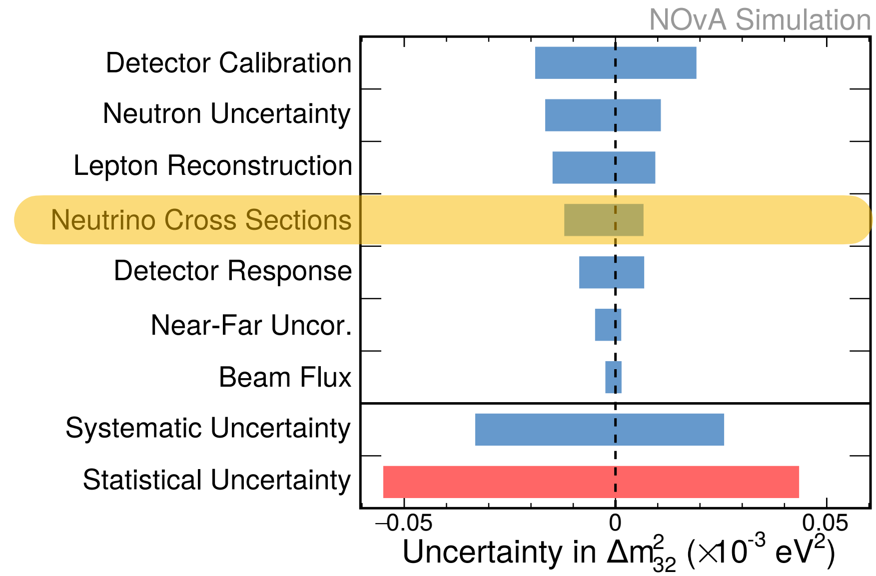
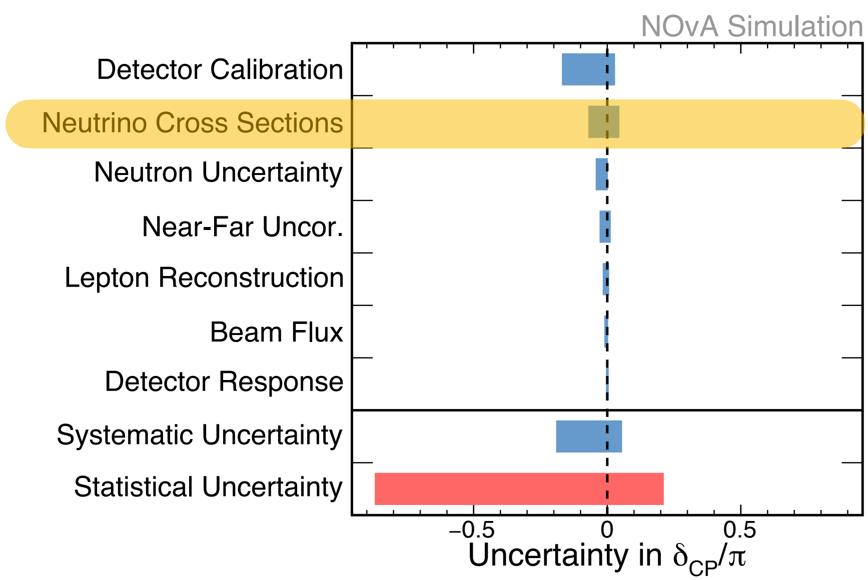


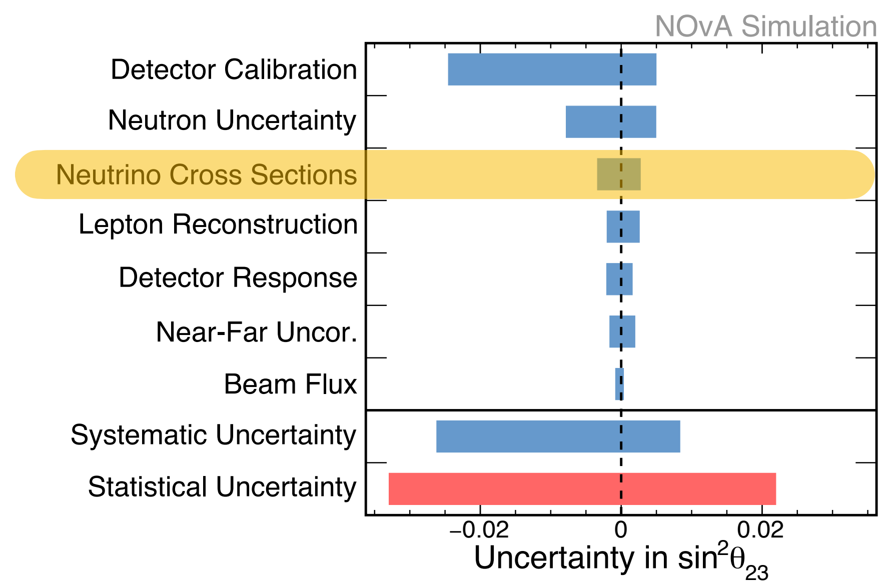


NOvA "3flavor" and extrapolation

- Systematic uncertainties are ν_μ disappearance: Δm^2_{32}, δ_{CP} & $\sin^2\theta_{23}$.
- **Extrapolation reduces impact of cross section uncertainties.**
- Also reduces strain on NOvA's prediction generation.

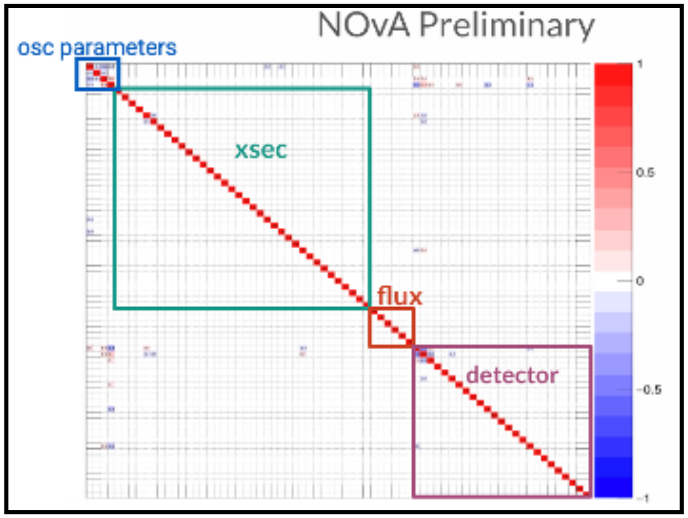


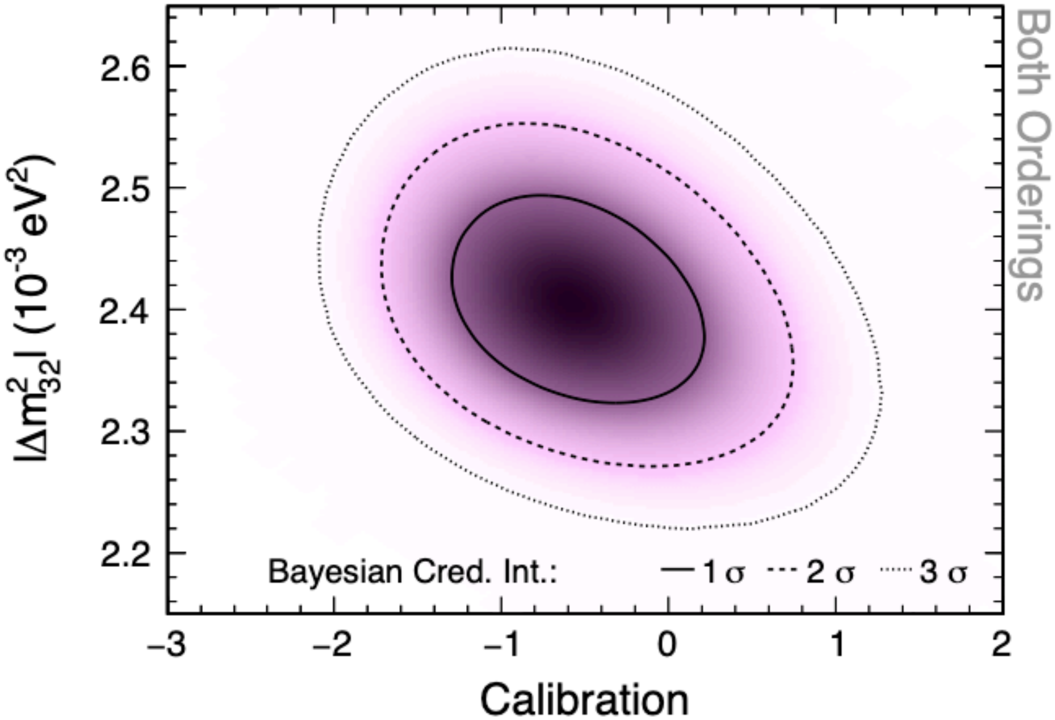




Extrapolation

- Also reduces the covariances between parameters as well.
- One of note — **calibration systematic** and Δm^2_{32}.
  - “Horizontal”, energy-based systematic, expected to impact this parameter.





NOvA — T2K

Cross Section Model

- As the underlying physics is fundamentally the same, we expect correlations
- Different neutrino interaction models
  - optimized for different energy ranges
- Systematics are designed for individual models and analysis strategies

❑ Impact of correlations is negligible on the results at the current statistical significance.

❑ Merits continued investigations for higher data exposures.

Cross-section: Impact of alternate models

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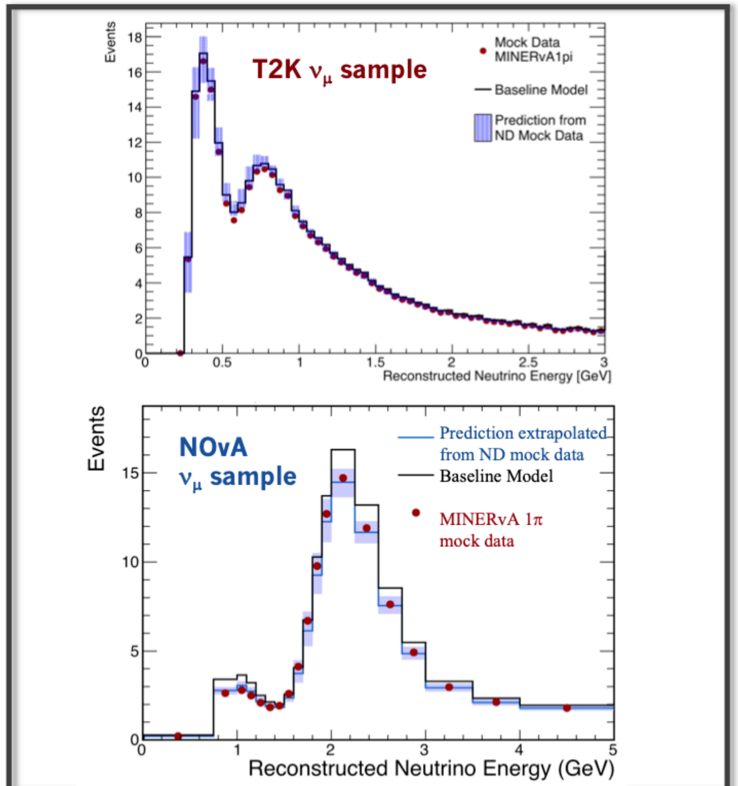
- Evaluate the robustness of the fit against various alternate models
- Generated simulated fake data using reweighting to alternate models for both the near and far detector, then analyze the credible intervals of the full joint-fit
- Pre-decided thresholds for bias:
  - Change in the width of the 1D intervals <10%
  - Change in central value < 50% of systematic uncertainty
- Example: Suppression in single pion channel based on tune to the MINERvA data*



*Phys. Rev. D 100, 072005 (2019)

NOvA — T2K

Global Comparisons - Δm^2_{32}

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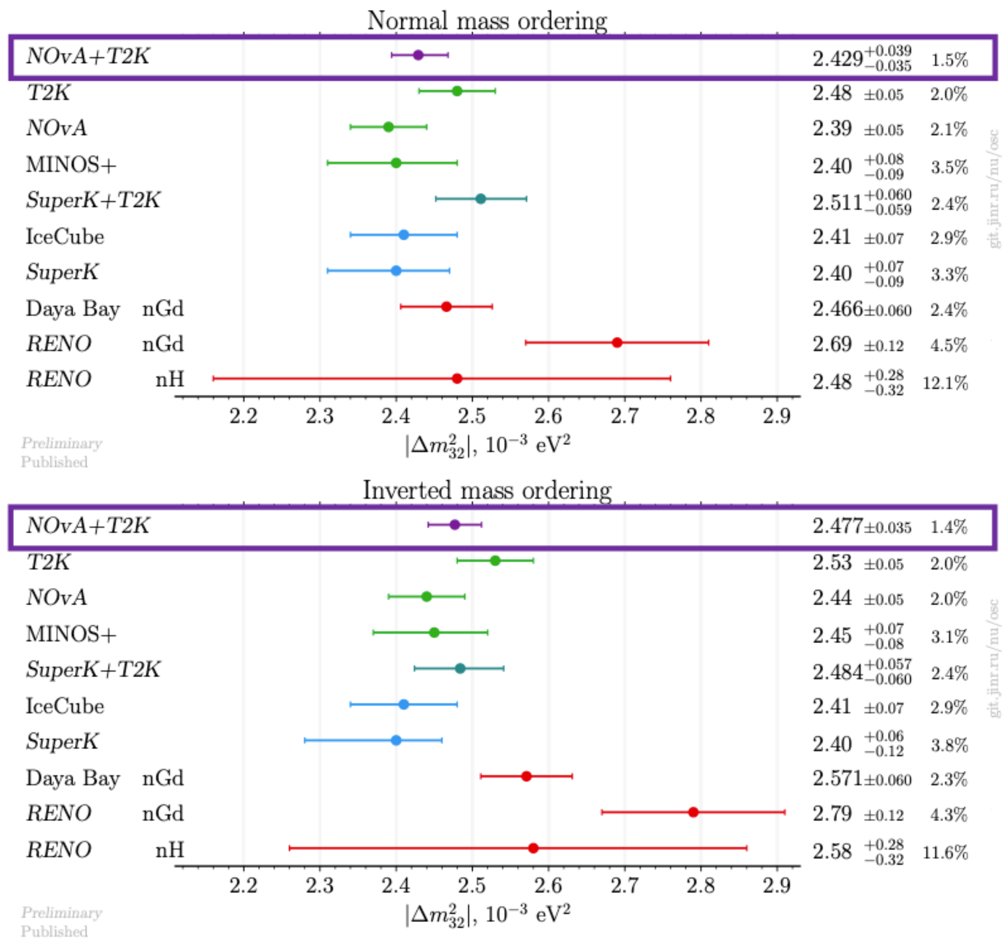
- This analysis has the **smallest uncertainty on $|\Delta m^2_{32}|$** as compared to other previous measurements.



Joint Analysis Results | Zoya Vallari, Caltech | Feb 16, 2024

Cross sections

- NOvA has several cross sections analyses.
- More are in the works!
- Look at an example.

ν_μ CC Low-E_{had}

Differential

p_μ **and** $\cos\theta_\mu$

Fermilab Wine + Cheese

Feb. 2024

Triple Differential

ν_μ CC

E_{avail} **,** $\cos\theta_\mu$ **,** T_μ

Fermilab Wine + Cheese

Apr. 2024

ν_μ CC $|\vec{q}|$-E_{avail}

Differential

$|\vec{q}|$ **and** E_{avail}

Fermilab Wine + Cheese

Feb. 2024

ν_e CC inclusive

Differential

E_e **and** $\cos\theta_e$

ν_μ CC inclusive

Differential

p_μ **and** $\cos\theta_\mu$

ν_μ CC π^0

Single Differential

p_μ , $\cos\theta_\mu$, p_π , $\cos\theta_\pi$,

Q^2 , W

2p2h focused analyses

ν_μ CC Low-E_{had}

Differential p_μ and $\cos\theta_\mu$

select: 1 track

$T_p \leq 250$ **MeV**

$T_\pi \leq 175$ **MeV**

Fermilab Wine + Cheese
Feb. 2024

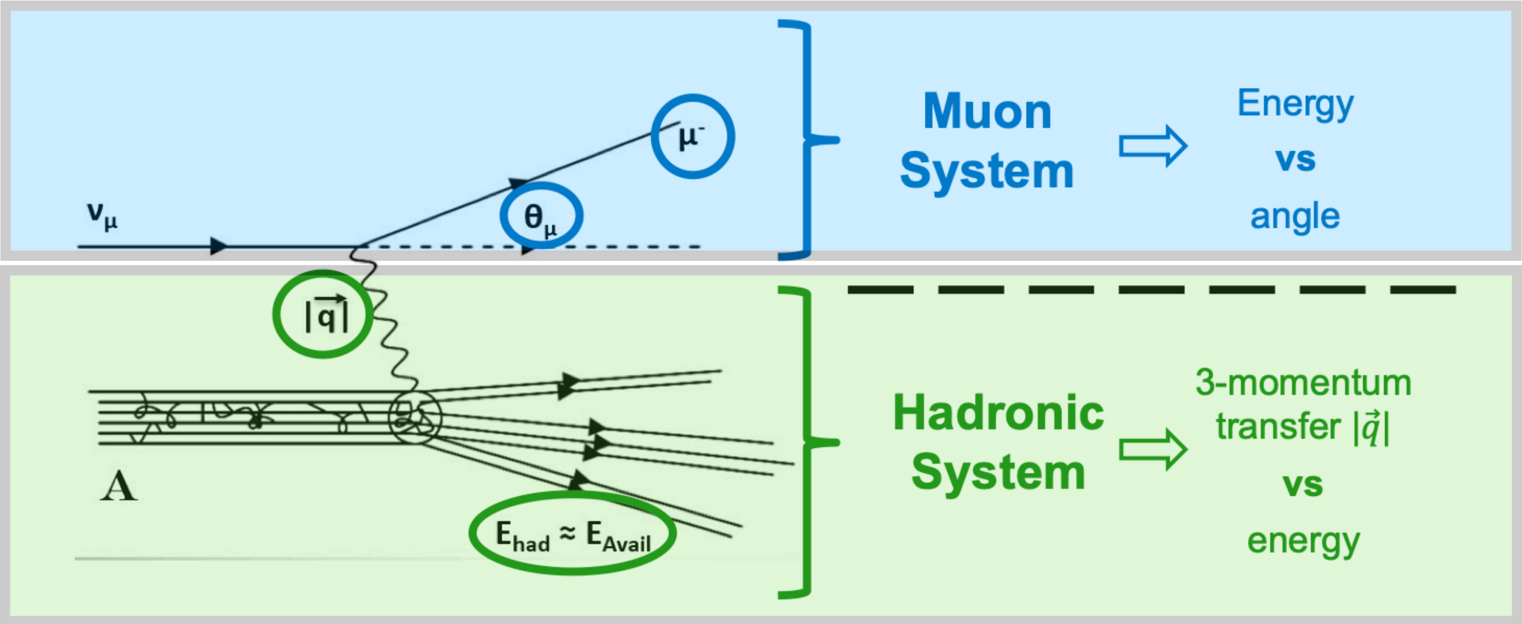
ν_μ CC $|\vec{q}|$-E_{avail}

Differential
$|\vec{q}|$ and E_{avail}

Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

Same NOvA 2p2h tune procedure, different model**: Empirical MEC.**



Single detector analyses

Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

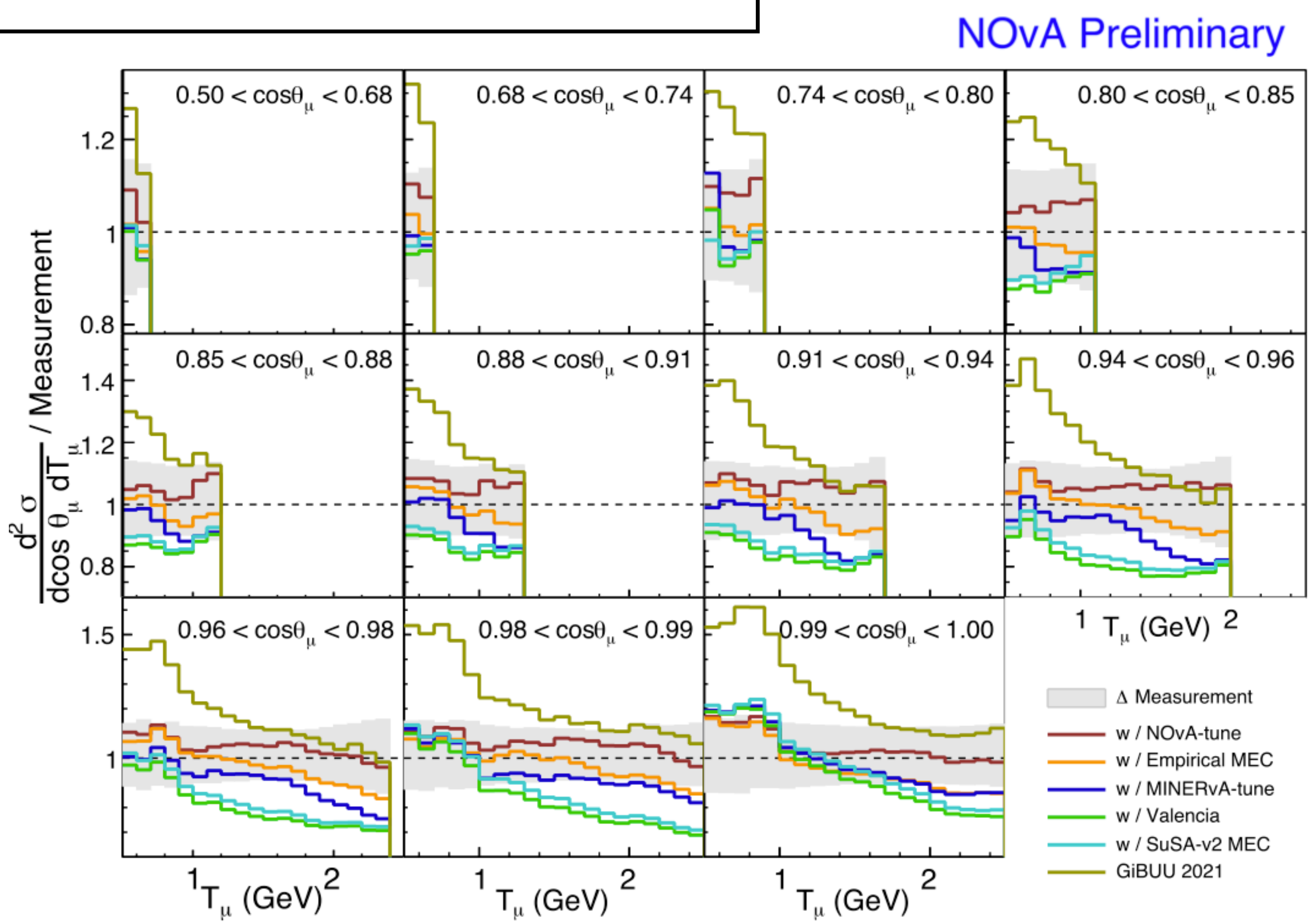
ν_μ CC Low-E_{had}

select: 1 track

$T_p \leq 250$ **MeV**

$T_\pi \leq 175$ **MeV**

- Measure the cross section with other 2p2h models.
- GiBUU is most discrepant in this analysis.
- SuSA-v2 and Valencia produce a similar result.



Single detector analyses

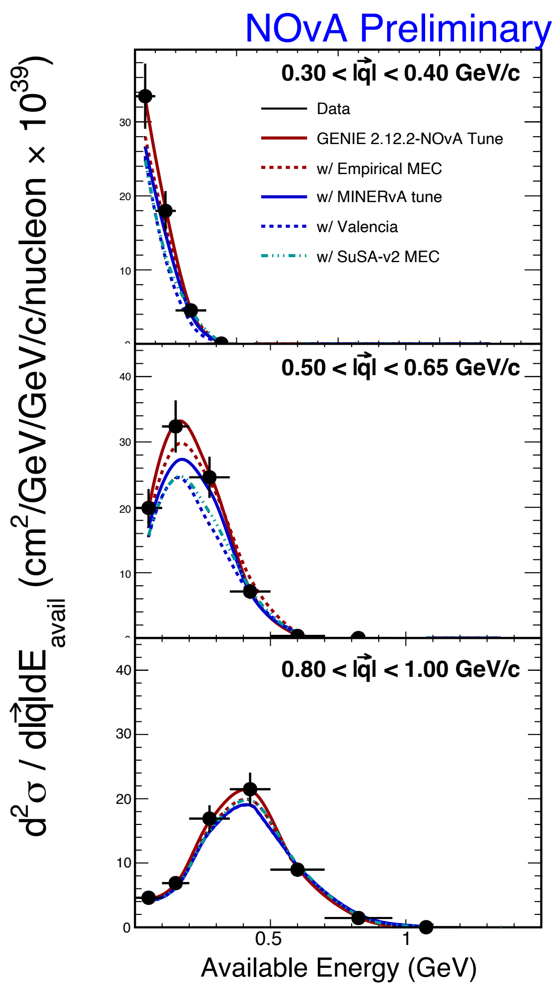
ν_μ CC $|\vec{q}|$-E_{avail}

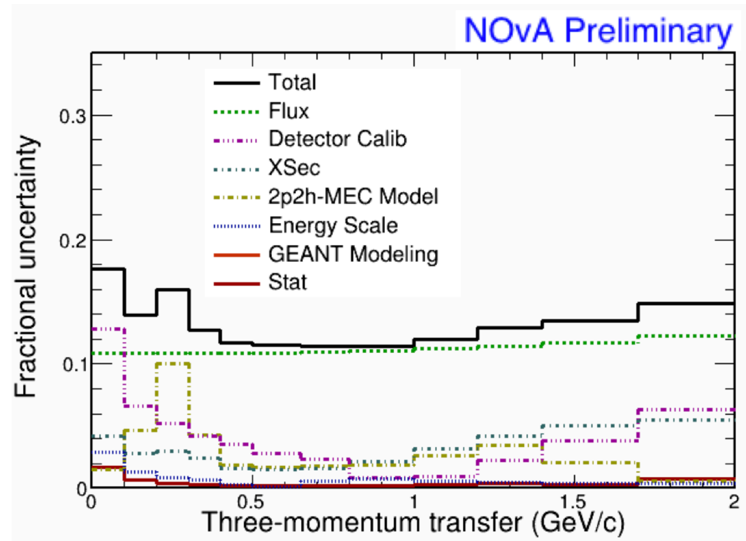
Differential
$|\vec{q}|$ and E_{avail}

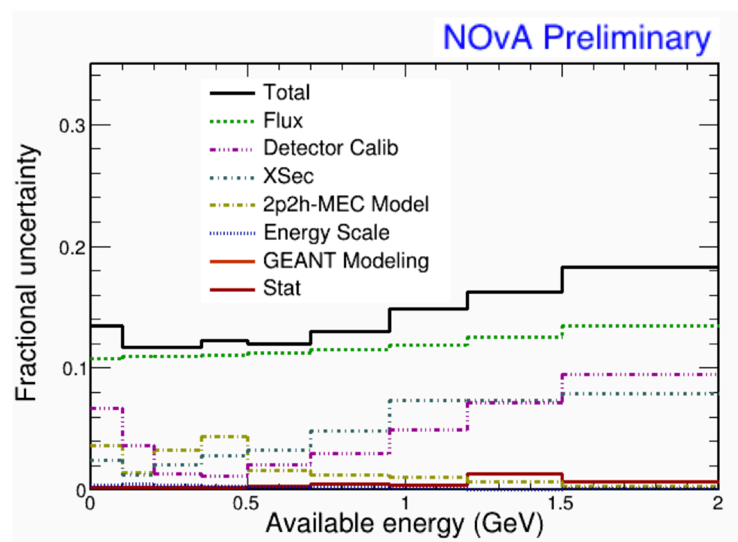
- Right, fractional uncertainty from hadronic analysis.
- Middle, predictions made with different 2p2h models.

Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

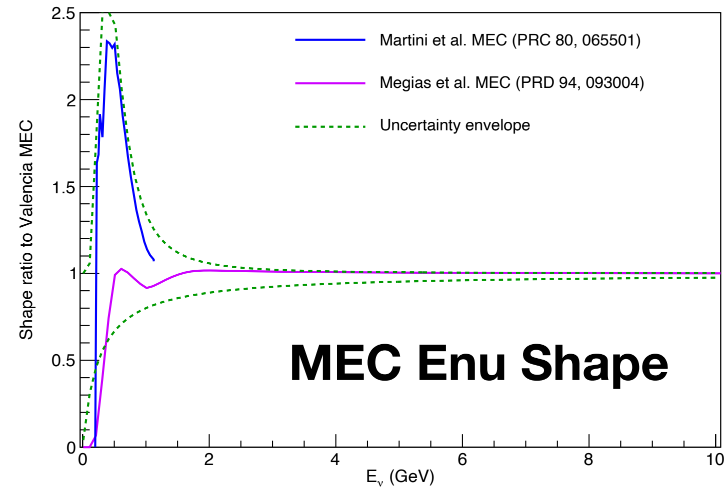


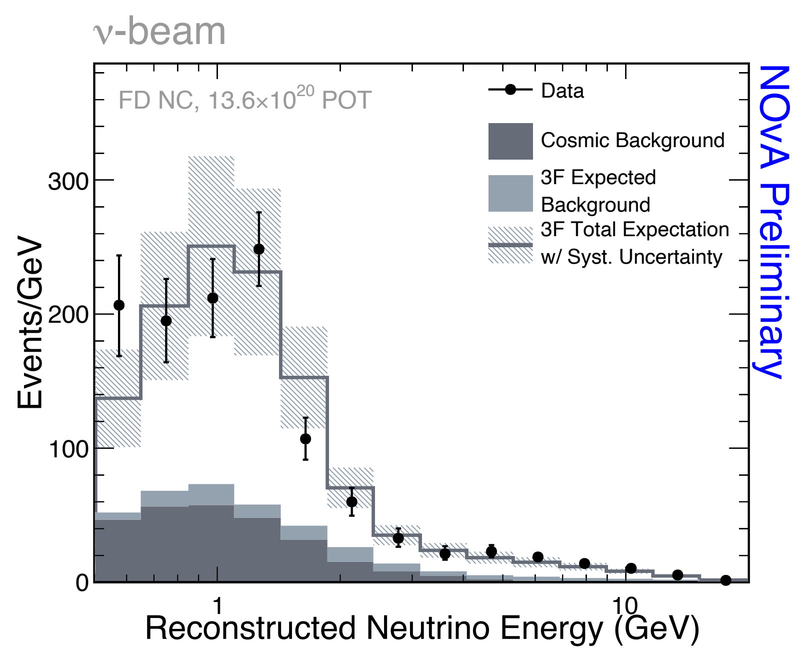




MEC uncertainty

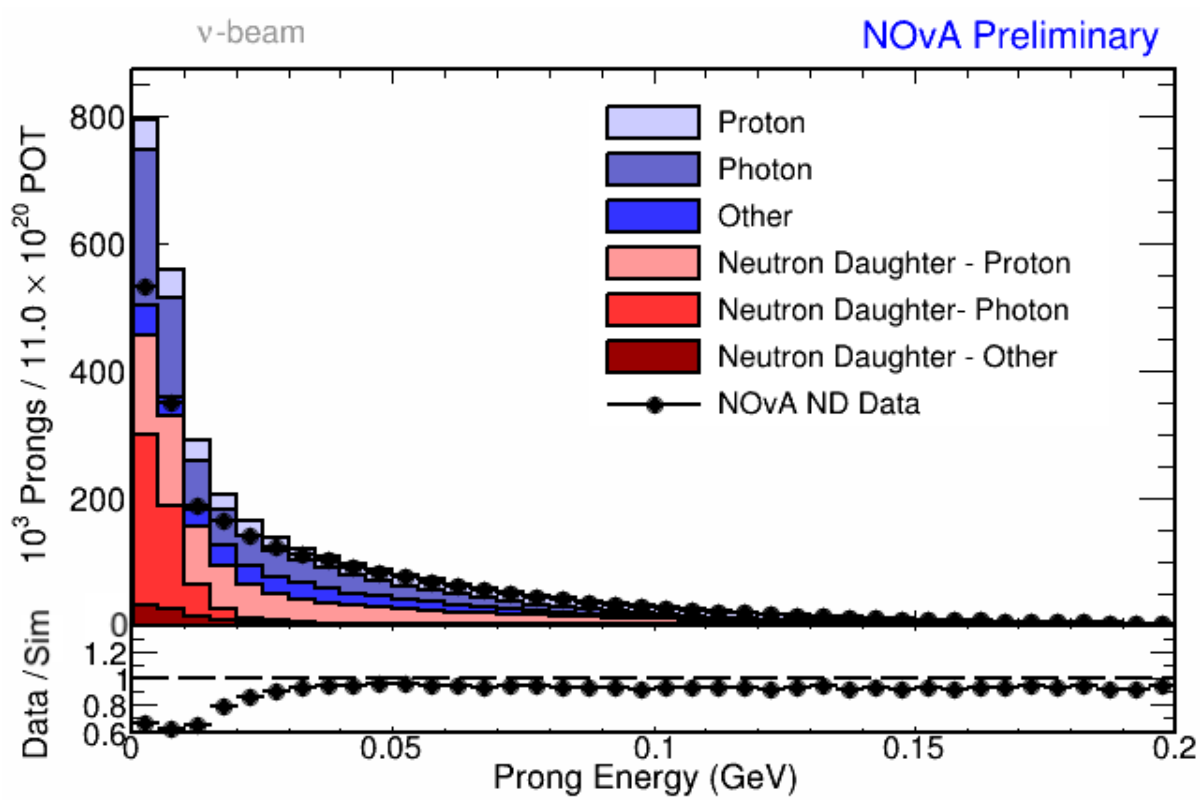
- Sterile analysis has special treatment for CC MEC:
  - Normalization systematic:
    - 100% on Valencia prediction.
  - Shape systematic:
    - Generated from NOvA tune — reliant on NOvA data.
  - **Use model spread.**
    - 1000 random universes of SuSA and Dytman weighted by Valencia in (q_3,q_0) space.
      - Correlation matrix made and PCA — 2 principal components used.
    - Bottom, error budget from the analysis.





Neutron Response

- We correct the data-MC disagreement in neutron-enhanced samples.
- Use this correction as the uncertainty.
  - Geant suggests over-production of photons at low prong energy.
  - Hope to improve this with more physics driven modeling.



Two-detector fits in NOvA

- This approach has received attention recently.
- Investigated NOvA ND data and MC with new scrutiny.
- Has initiated development of new degrees of freedom.
- An area NOvA intends to pursue in future.

Constraining neutrino oscillation and interaction parameters with the NOvA Near Detector and Far Detector data using Markov Chain Monte Carlo

A dissertation submitted by

Michael Dolce

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Constraining neutrino interaction uncertainties for oscillation measurements in the NOvA experiment using Near Detector data

by

Maria Martinez Casales

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

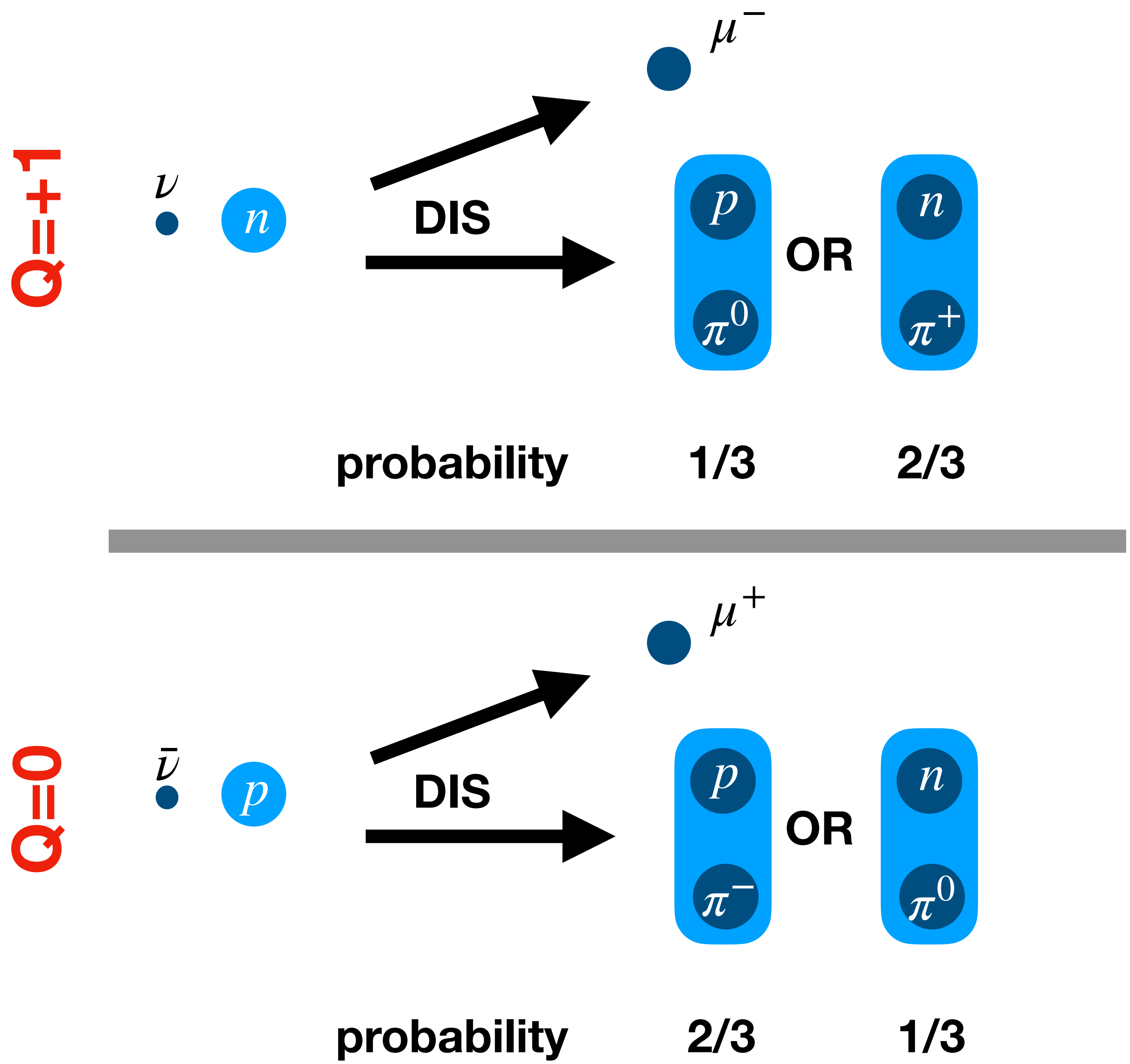
A new RES systematic

- Adjust the relative νp / νn RES cross section.
- Attempt to address RES/DIS interactions — especially those with pions.

Δ decays....	$+3\sigma$ shift....
$\nu + p \rightarrow \mu^- + \Delta^{++}$	
$\Delta^{++} \rightarrow p + \pi^+$	more events with π
$\nu + n \rightarrow \mu^- + \Delta^{+}$	
$\Delta^{+} \rightarrow \pi^+ + n$	less events with π
$\Delta^{+} \rightarrow \pi^0 + p$	less events with p
$\bar{\nu} + p \rightarrow \mu^+ + \Delta^{0}$	
$\Delta^{0} \rightarrow \pi^0 + n$	less events with p & prong
$\Delta^{0} \rightarrow \pi^- + p$	more events with π
$\bar{\nu} + n \rightarrow \mu^+ + \Delta^{-}$	
$\Delta^{-} \rightarrow n + \pi^-$	less events with p

A new DIS systematic

- In GENIE, a ν CC DIS, with final state Q=+1,0, and multiplicity=2 **has fixed probabilities**:
    - proton = 1/3.
    - neutron = 2/3.
- Associated with isospin amplitudes.
- Allow flexibility in the final states → topology.



NOvA cross section uncertainties

QE

****
RPAShapeenh2020
RPAShapesupp2020
ZExpAxialFFSyst2020_EV1
ZExpAxialFFSyst2020_EV2
ZExpAxialFFSyst2020_EV3
ZExpAxialFFSyst2020_EV4
ZNormCCQE

RES

LowQ2RESSupp2020
RESDeltaScaleSyst
RESOtherScaleSyst
RESvpvnRatioNuXSecSyst
RESvpvnRatioNubarXSecSyst
MaCCRES
MvCCRES
MaNCRES
MvNCRES
RDecBR1gamma
RDecBR1eta
Theta_Delta2Npi

MEC

MECShape2020GSFNu
MECShape2020GSFAntiNu
MECEnuShape2020Nu
MECEnuShape2020AntiNu
MECInitStateNPFrac2020Nu
MECInitStateNPFrac2020AntiNu

DIS

DISvpCC0pi_2020
DISvpCC1pi_2020
DISvpCC2pi_2020
DISvpCC3pi_2020
DISvpNC0pi_2020
DISvpNC1pi_2020
DISvpNC2pi_2020
DISvpNC3pi_2020
DISvnCC0pi_2020
DISvnCC1pi_2020
DISvnCC2pi_2020
DISvnCC3pi_2020
DISvnNC0pi_2020
DISvnNC1pi_2020
DISvnNC2pi_2020
DISvnNC3pi_2020
DISvbarpCC0pi_2020
DISvbarpCC1pi_2020
DISvbarpCC2pi_2020
DISvbarpCC3pi_2020

DISvbarpNC0pi_2020
DISvbarpNC1pi_2020
DISvbarpNC2pi_2020
DISvbarpNC3pi_2020
DISvbarnCC0pi_2020
DISvbarnCC1pi_2020
DISvbarnCC2pi_2020
DISvbarnCC3pi_2020
DISvbarnNC0pi_2020
DISvbarnNC1pi_2020
DISvbarnNC2pi_2020
DISvbarnNC3pi_2020
DISNuHadronQ1Syst
DISNuBarHadronQ0Syst
FormZone2020GSF
AhtBY
BhtBY
CV1uBY
CV2uBY

FSI

hNFSI_FateFracEV1_2020GSF
hNFSI_FateFracEV2_2020GSF
hNFSI_FateFracEV3_2020GSF
hNFSI_MFP_2020GSF

Other

radcorrnue
radcorrnuebar
2ndclasscurr
MaNCEL
EtaNCEL
COHCCScale2018
COHNCScale2018
AGKYxF1pi
AGKYpT1pi