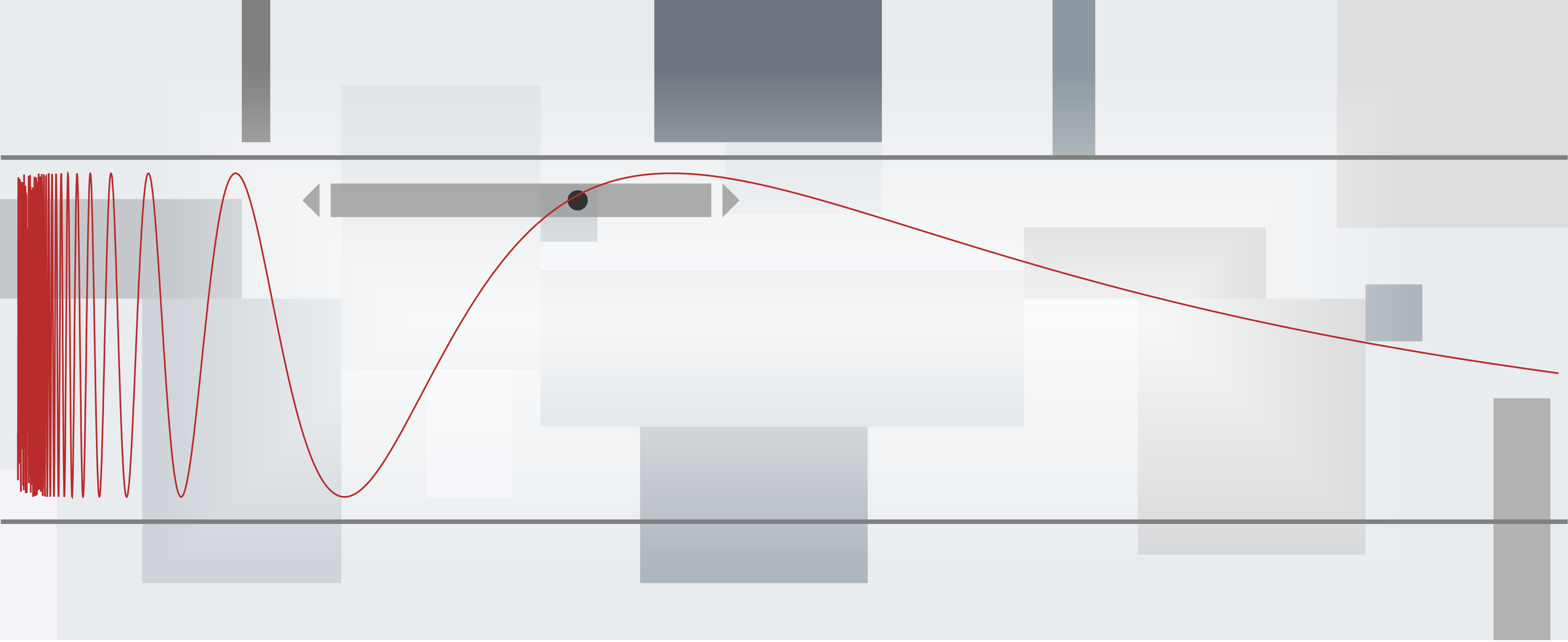


Cross section Uncertainties in NOvA Analyses

Jeremy Wolcott
Tufts University
on behalf of the NOvA collaboration

ECT* Workshop on ν Interactions
October 22, 2024

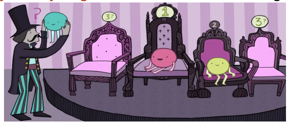
Context

[NOvA physics scene & expt] — [Base cross section model]

NOvA physics scene

NOvA physics scene

Symmetry Magazine / Sandbox Studio, Chicago



 vs 

Which way are the
neutrino states ordered?

$\nu_3=$ 

ν_e ν_μ ν

Do **ν_μ/ν_τ mix equally**
into the ν mass states?

$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

Do neutrinos exhibit
CP violation?

① 3-flavor neutrino oscillations

NOvA physics scene

Symmetry Magazine / Sandbox Studio, Chicago

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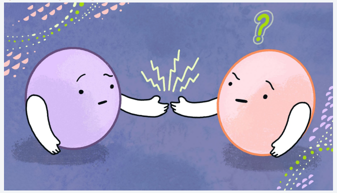
Are there **light sterile neutrinos**?

particlezoo.net

Symmetry Magazine / Corinne Mucha / Sandbox Studio



$$H = UH_0U^\dagger + H_{matter} \ldots + H_{NSI}??$$

Do we fully understand **neutrino propagation in matter**?

② Neutrino oscillations beyond PMNS

NOvA physics scene

Symmetry Magazine / Sandbox Studio, Chicago

Which way are the **neutrino states ordered**?

① 3-flavor neutrino oscillations

ν_e = ν_e ν_μ ν_τ

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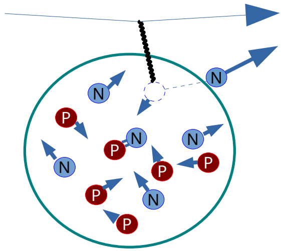

Is our picture of **neutrino scattering** sufficient?

③ Neutrino scattering

NOvA physics scene

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Symmetry Magazine / Sandbox Studio, Chicago

vs

Which way are the **neutrino states ordered**?

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Symmetry Magazine / Corinne Mucha / Sandbox Studio

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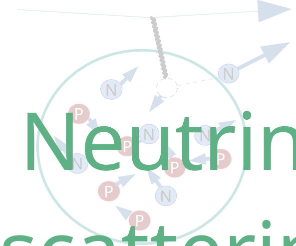
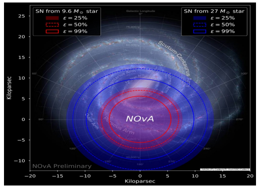
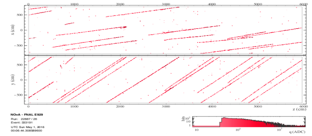


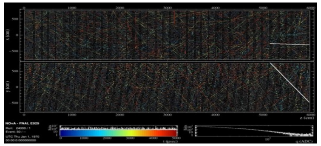
Is our picture of **neutrino scattering** sufficient?



Will we observe a **galactic supernova**?



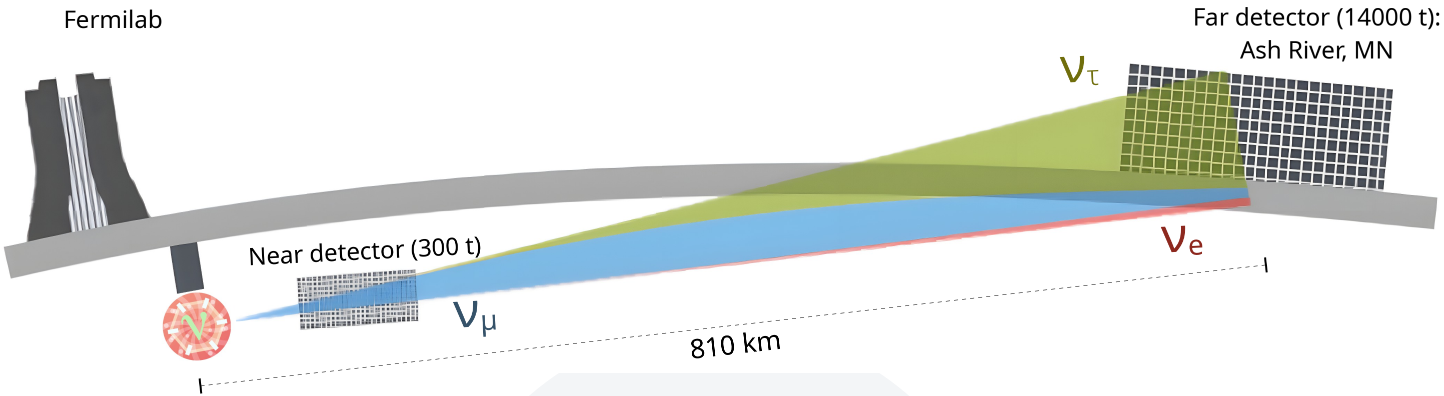
What can we learn from **cosmic muons**?

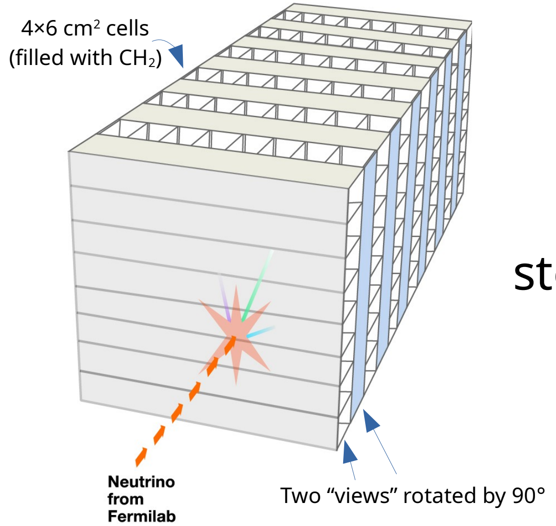


Do we see **magnetic monopoles** or other exotic phenomena?

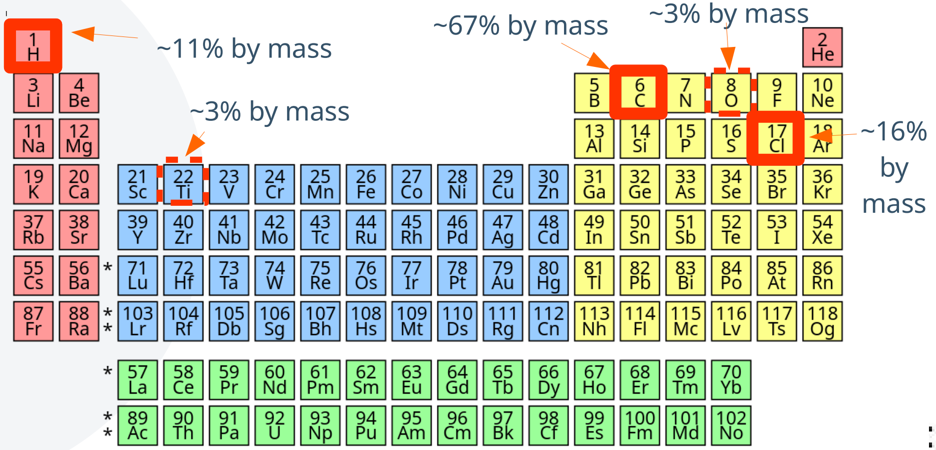
④ Opportunistic/ exotic physics

NOvA: apparatus & νs



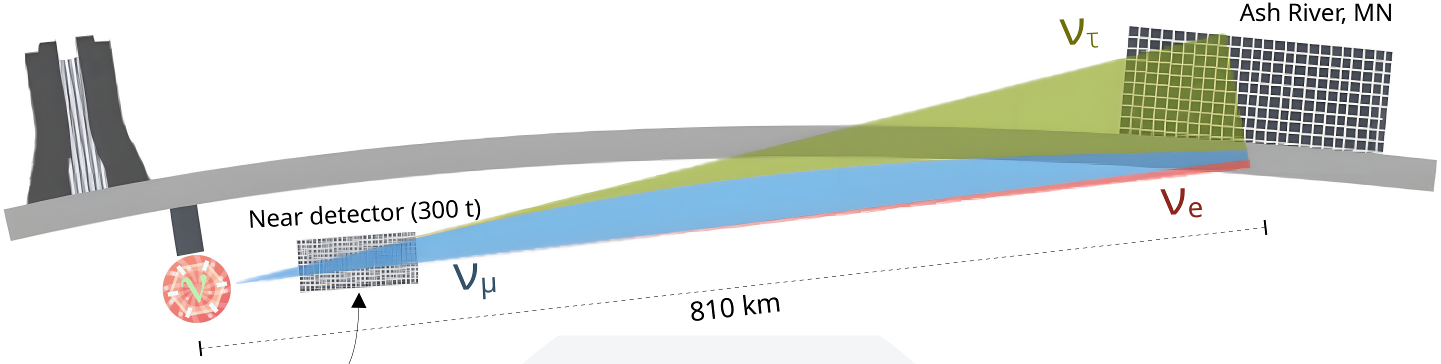


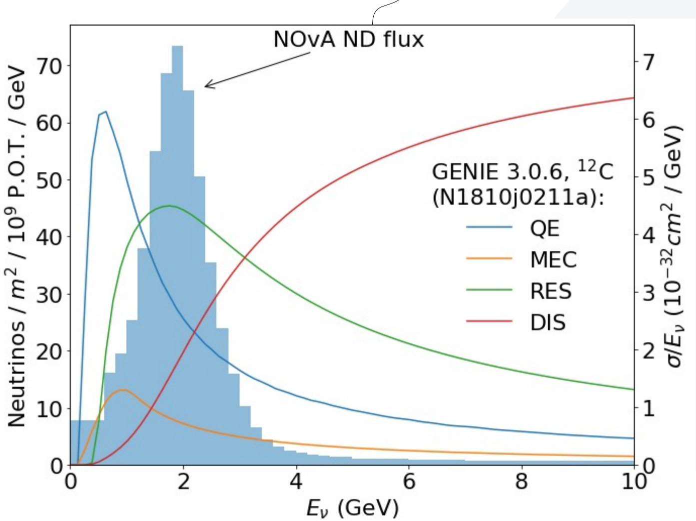
One moderate &
one *really big*
stereoscopic detector…



… made of PVC and filled with CH_2…

NOvA: apparatus & νs



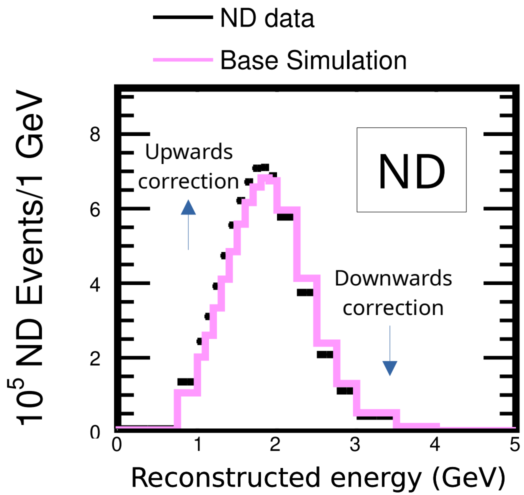


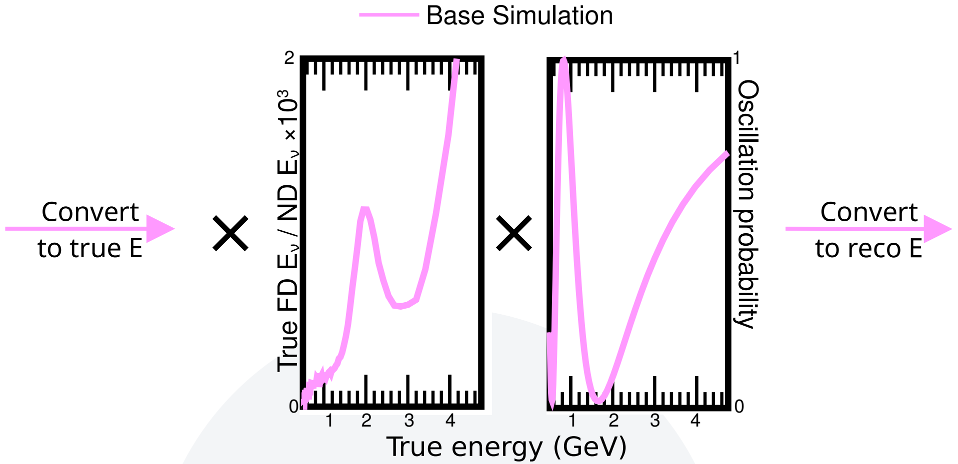
… and illuminated with a ~2 GeV ν_μ beam

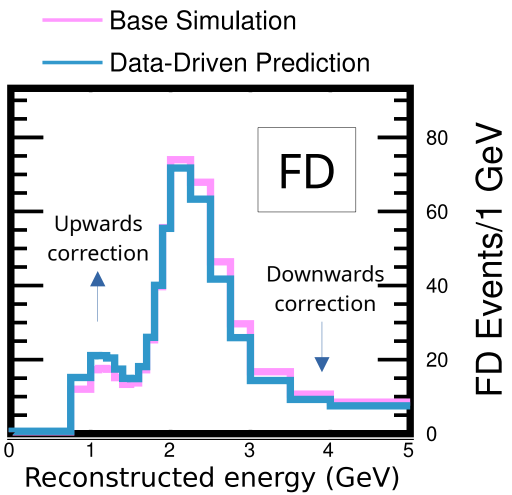
Analysis context

- Most uncertainties developed in context of **3-flavor oscillations**
  - Rely on **strong** ND-FD correlations/cancellation via "extrapolation" technique → next slide
  - Uncertainties typically chosen conservatively to "bracket possibilities"
  - Central value of model less important than plausible bounds from uncertainties
- Other customers (beyond-PMNS osc., cross section measurements) develop **separate uncertainties as needed**
  - … where ND-data-driven uncertainties risk biasing results
  - … where other ν interaction processes (e.g.: NC) become dominant

Analysis context







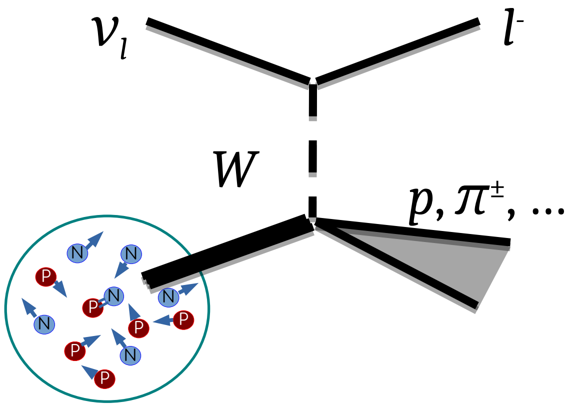
Correct ND simulation
to agree with data in reco E_ν…

… **via Far/Near transformation** that comprises **well understood effects** (beam divergence, detector acceptance) + **oscillations**

… results in **constrained FD E_ν prediction** highly correlated with ND correction

3-flavor osc., NSI "**extrapolation**" analysis is *data-driven*
and can correct even "unknown unknowns",
so long as the base model isn't "too far" off

Base cross section model



Base simulation: GENIE 3.0.6

- We begin with a "theory-driven" set of models* …

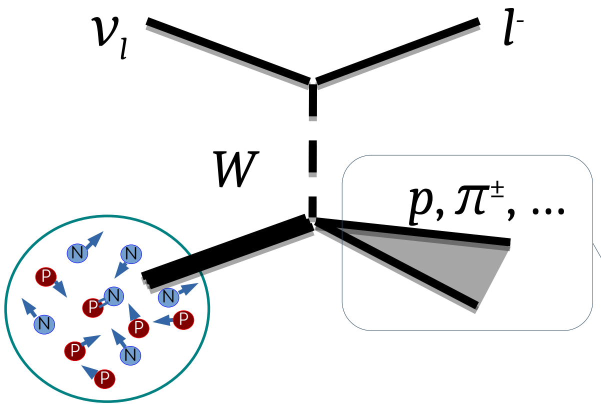
  … but it agrees poorly with our data (as do all other stock model configurations we tested) …

  … so we apply *post hoc* "tuning" to get the model "close enough"

QE	Multinucleon	RES	DIS	FSI
València 1p1h w/ Z-expansion axial form factor	València MEC	Berger-Sehgal	Bodek-Yang + AGKY/Pythia	hN semi-classical cascade

* We call our model collection N18_10j_00_000. It is built by starting with GENIE's G18_10b_00_000 and substituting the Z-expansion QE axial form factor for the dipole one. This combination was not available in the 3.0.6 release, but it could be in future versions.

Base cross section model



QE	València 1p1h w/ Z-expansion axial form factor
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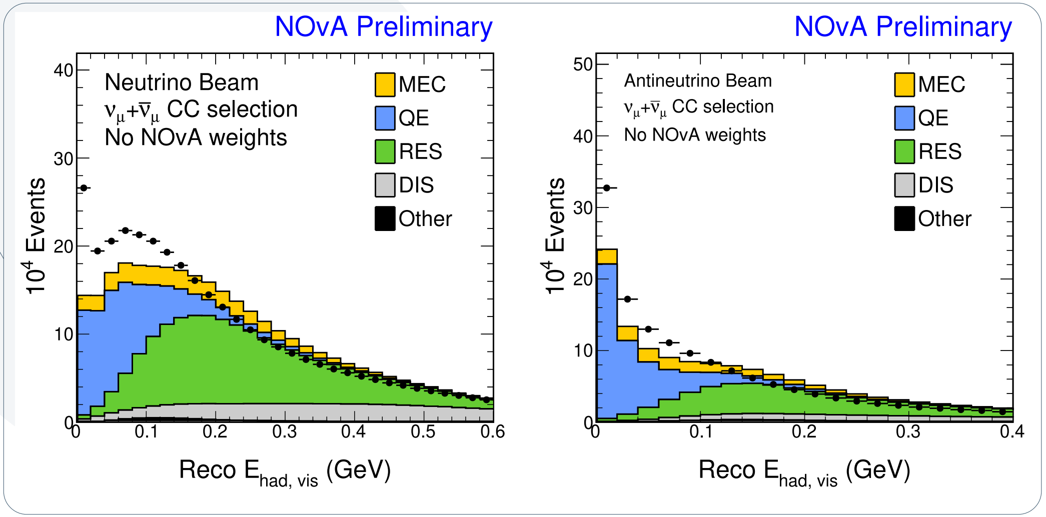
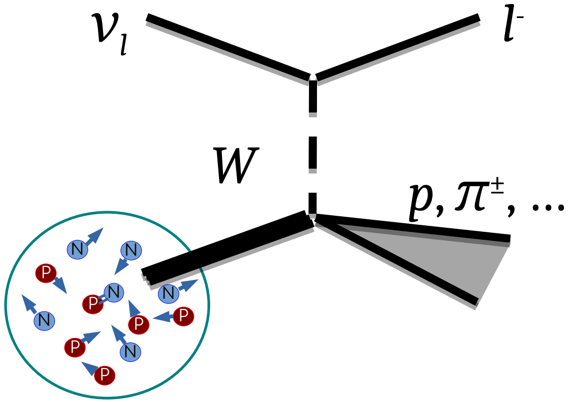


Base cross section model



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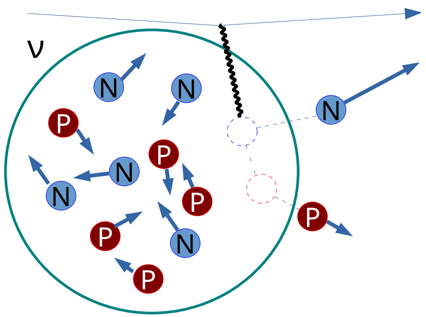
València 1p1h w/ Z-expansion axial form factor	València MEC	Berger-Sehgal	Bodek-Yang + AGKY/Pythia	hN semi-classical cascade

For analyses that use “extrapolation”,
apply custom “tuning” in two places
in tandem with custom uncertainties

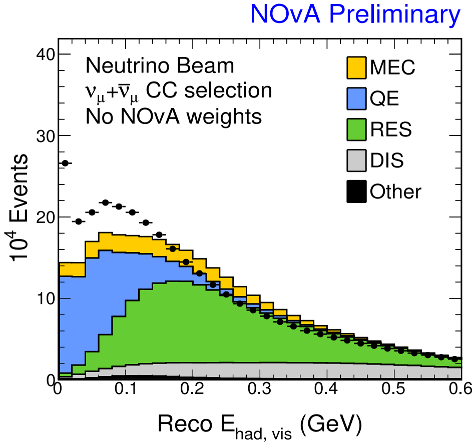
Tuning: multinucleon



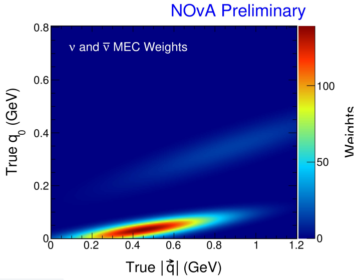
"2p2h"

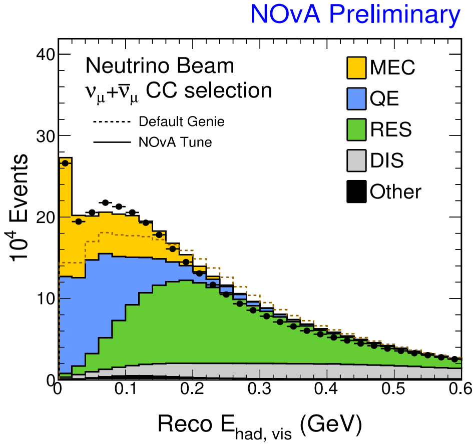
Knock out two nucleons
with an elastic-like interaction.

Most (?) uncertain part of the model…



Fitted double-Gaussian weights applied to true CC MEC





Employ **fits to NOvA ND data** to get in the ballpark
[detailed discussion of technique with different base model
in NuSTEC CTGWG Seminar Dec. 14, 2022 (J. Wolcott)]

Dedicated uncertainties address dependence
on the other components of prediction (QE, RES)
(more shortly)

[Note: tuning procedure is used for **3-flavor osc., NSI.**
But **Sterile ν, cross sections** use *unaltered* Valencia base model.]

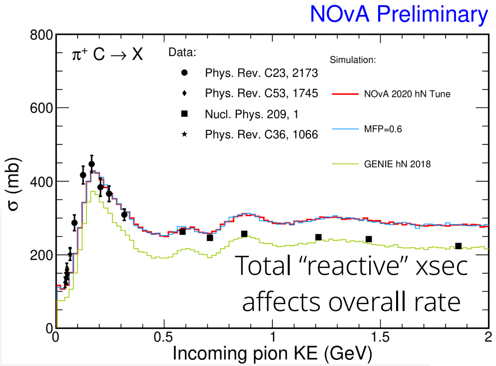
Tuning: FSI

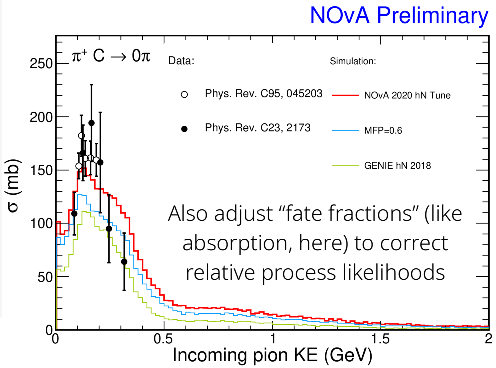
- FSI model choice: **"hN"**
  - Propagates hadrons through nucleus in finite steps
  - Interaction probabilities simulated according to Oset quantum model
  - More rigorous foundation than "hA" effective model?...
- Challenge: **hN not directly reweightable**
  - Addressed with BDT reweighting technique adapted from DUNE (see overflow)

Unlike MEC tuning, FSI adjustment is used by *all* analyses since it does not depend on ν data

Adjust central value to better match $\pi^{\pm}$ scattering data

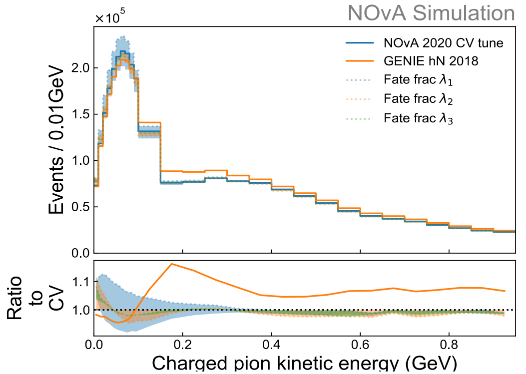
in regions most relevant to NOvA ($T_{\pi} \lesssim$ 500 MeV)

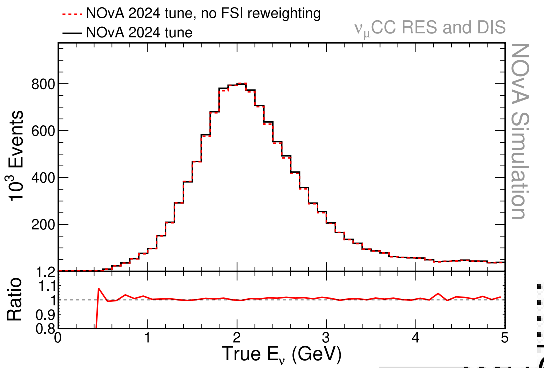




Impact

- 5-10% effect on pion kinematics (more on uncertainties shortly)
- Ultimately subdominant for calorimetric E_{ν} reco. used in NOvA

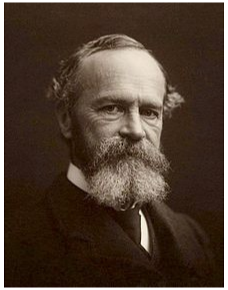




Current
cross section uncertainties

[Philosophy] — [GENIE knobs] — [Bespoke knobs]

Cross section philosophy



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

- We have not sought “the right” cross section model – **just a *functional* model**
  - “Extrapolation” insulates against many potential pitfalls, only requires being “close enough”
  - Viable theoretical underpinnings are not always needed (so long as data description is reasonable), though unquestionably preferred
  - NOvA detector design is relative coarse (by modern standards) → hadronic systems are poorly resolved
  - Cross section measurements help us gauge how far off we are
- We typically choose ***representative* uncertainties**
  - Uncertainties to gauge whether “extrapolation” has *weaknesses*—don’t need an exhaustive collection to get the right answer
  - “Bracketing” space of possibilities is usually sufficient
  - Fake data studies with out-of-model warping used to test for possible issues
- We have taken a **NOvA-centric view to which “holes” to prioritize** plugging first
  - 1p1h/2p2h 0π $\overset{?}{>}$ RES 1π ≫ DIS/Nπ
  - $\nu \overset{?}{>} \bar{\nu}$

Types of uncertainties

“Inherited”

GENIE-Reweight

“NOvA Bespoke”

Based on external info

Based on NOvA data

GENIE-Reweight uncertainties

CC QE

Dipole FF masses M_A, M_V

Coulomb off/on

Z-exp. FF coeffs a_0, a_1, a_2, a_3, a_4

RPA off/on

CC RES

Dipole FF masses M_A, M_V

$\Delta \rightarrow N\gamma$ branching fraction

Δ polarization

$\Delta \rightarrow N\eta$ branching fraction

CC "SIS"

$\{\nu,\bar{\nu}\} \times \{n,p\} \times \{1,2\}\pi$ normalization

CC DIS

Bodek-Yang A_{ht}, B_{ht}, C_{V1u}, C_{V2u}

AGKY $x_F^{1\pi}$, $p_T^{1\pi}$

CC MEC

np fraction of init. state

NN pair "decay" angle

fraction of MEC from intermediate Δ

kinematic shape

COH

Axial mass M_A

NC norm

Effective nuclear radius R_0

CC norm

hA FSI

Mean free paths λ_π, λ_N

"Fate fractions" f^π_{Inel}, f^π_{CEX}, f^π_{ABS}, $f^\pi_{\pi\ prod}$ f^N_{Inel}, f^N_{CEX}, f^N_{ABS}, $f^N_{\pi\ prod}$

… plus NC variants of many of these

GENIE comes bundled with a large suite of reweightable uncertainties

GENIE-Reweight uncertainties

CC QE

- Dipole FF masses M_A, M_V
- Coulomb lepton-nucl off/on
- Z-exp. FF coeffs a_0, a_1, a_2, a_3, a_4
- RPA off/on

CC RES

- Dipole FF masses M_A, M_V
- $\Delta \to N\gamma$ branching fraction
- Δ polarization
- $\Delta \to N\eta$ branching fraction

CC "SIS"

- $\{\nu, \bar{\nu}\} \times \{n,p\} \times \{1,2\}\pi$ normalization

CC DIS

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- AGKY $x_F^{1\pi}$, $p_T^{1\pi}$

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- np fraction of init. state
- NN pair "decay" angle
- fraction of MEC from intermediate Δ
- kinematic shape

COH

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- NC norm
- Effective nuclear radius R_0
- CC norm

hA FSI

- Mean free paths λ_π, λ_N
- "Fate fractions" f^π_{Inel}, f^π_{CEX}, f^π_{ABS}, $f^\pi_{\pi\,prod}$, f^N_{Inel}, f^N_{CEX}, f^N_{ABS}, $f^N_{\pi\,prod}$

… plus NC variants of many of these

For NOvA:

- We use **some** of these knobs as-is
- Some **others** are irrelevant for our chosen configuration
- We've implemented **our own knobs** that provide alternate behavior to many others

GENIE comes bundled with a large suite of reweightable uncertainties

Bespoke NOvA uncertainties

NOvA focus areas

- CCQE
  - Reimplementation of z-expansion a_1-a_4 to preserve correlations
  - RPA [predates similar GENIE knob]
- MEC
  - Kinematic shape [coupled to fitting]
  - E_ν dependence
  - np fraction [predates similar GENIE knob]
- RES
  - Low Q^2 suppression
  - Δ vs. non–Δ resonance composition
- Pion production [RES + {D/S}IS]
  - Charged vs. neutral baryon production
  - "SIS" channel normalizations

Making non-reweightable GENIE parameters reweightable

- hN FSI
- Hadronization formation zone

No comparable GENIE knob(s)

- ν_e / ν_μ
  - Radiative corrections
  - 2nd class currents

Replacing GENIE knobs that used to be broken

- Coherent
  - CC, NC norms

Bespoke NOvA uncertainties

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Making non-reweightable GENIE parameters reweightable

- hN FSI
- Hadronization formation zone

Replacing GENIE knobs that used to be broken

- Coherent

I'm going to explore these 3 further, where NOvA choices are more unique

(but feel free to ask about any others you're interested in as well)

Multinucleon uncertainties

Two separate use cases

ND provides *systematic control:*
3-flavor osc., NSI measurements

Fit-based uncertainty

Based on NOvA data

ND provides *signal*:
Sterile ν, cross section measurements

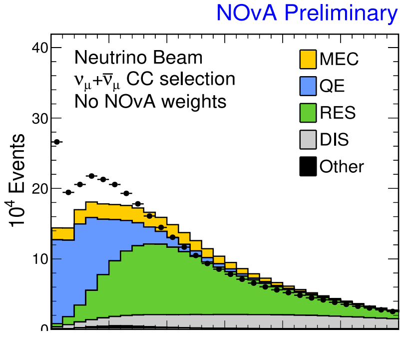
Model-spread uncertainty

Based on external info

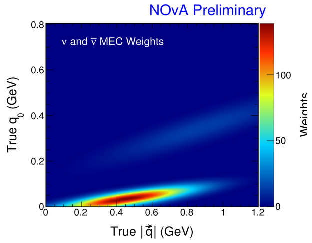
Multinucleon: fit-based unc.

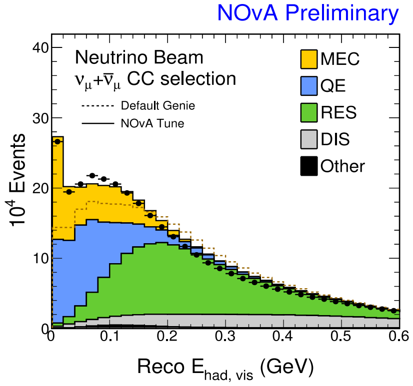
Recall:

central value fitted to ND data



Fitted double-Gaussian weights applied to true CC MEC





Multinucleon: fit-based unc.

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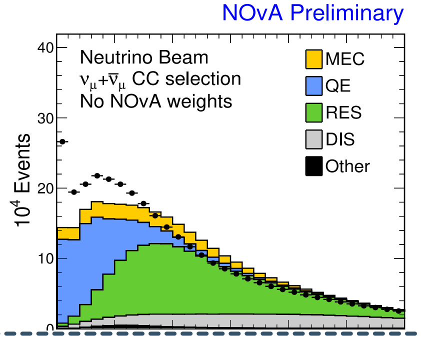
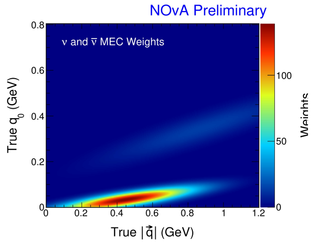
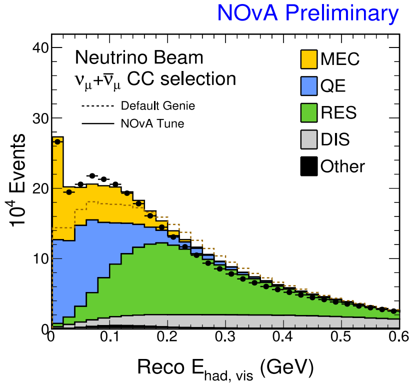


Fitted double-Gaussian weights applied to true CC MEC

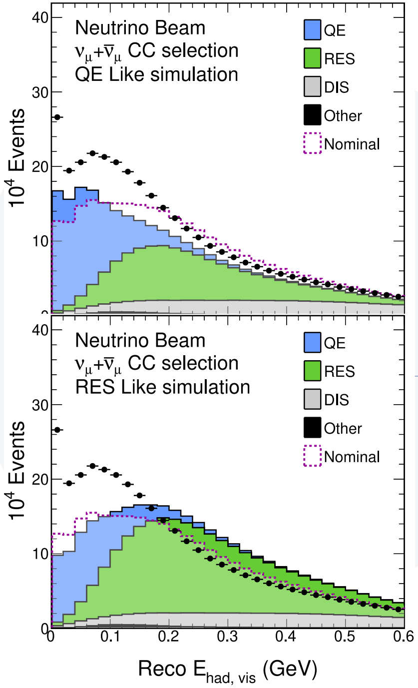




Re-perform fit, with alternate base models, for uncertainties

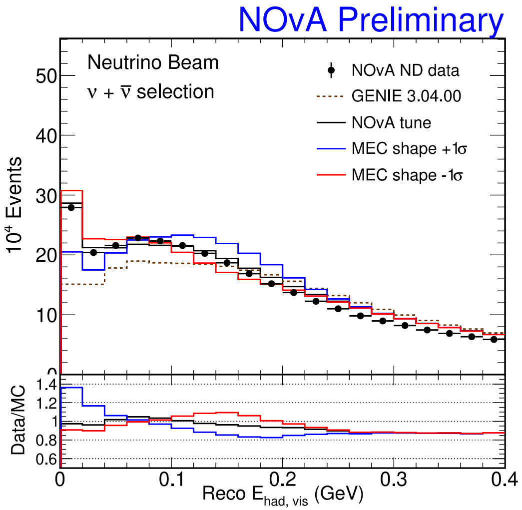
(interpolate between these extremes)

Based on NOvA data



Re-fit using "extreme" variations of QE, RES systematics to bracket impact on fitted MEC

(these alternate MEC predictions used as systematic uncertainties)



Multinucleon: model spread unc.

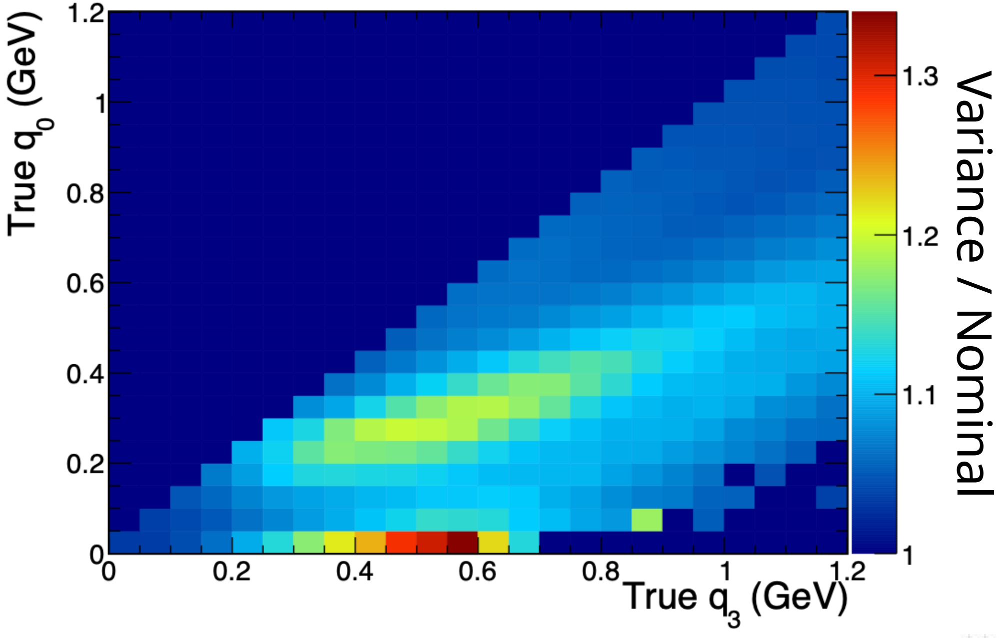
Based on external info

- Variance in (q_0, |**q**|) over 3 MEC models:

  SuSA, Valencia, GENIE “Empirical”

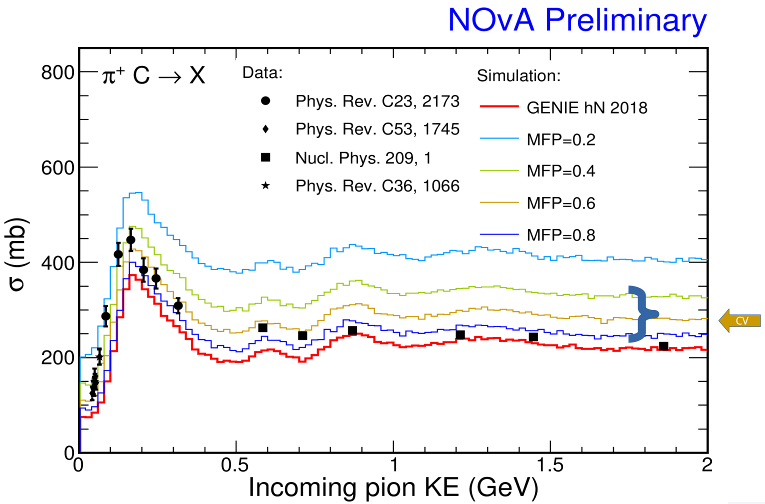
- Result just touches NOvA ND data at “+1σ”

  → but note less flexibility in “moderate q_0” region compared to “fitted” unc. (previous)



FSI: uncertainties

Based on external info

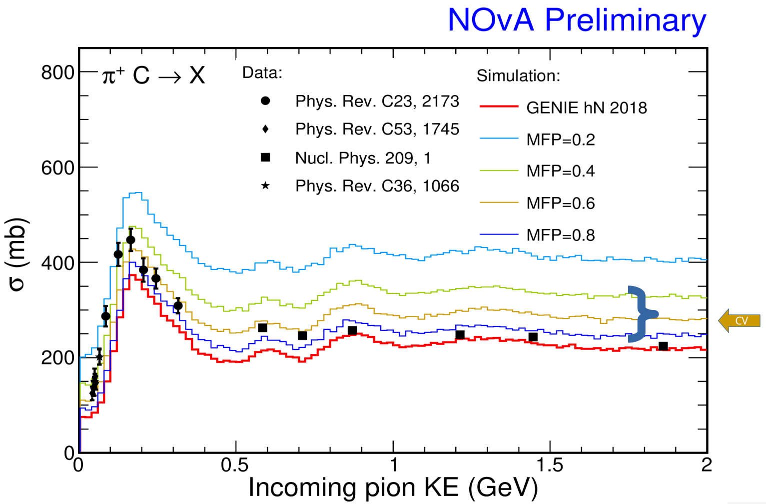


① It's straightforward to bracket the **mean free path** variations: f_{MFP}=0.4 and f_{MFP}=0.8

Use same "BDT reweight" technique as CV to implement in analysis

FSI: uncertainties

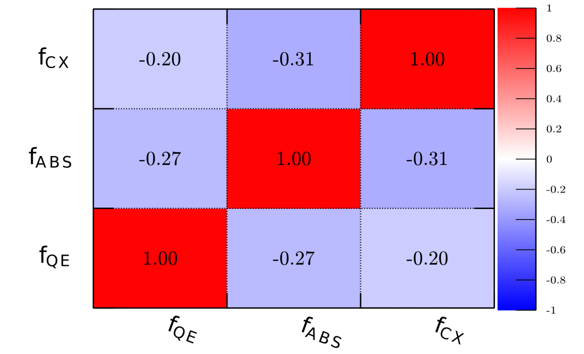
Based on external info



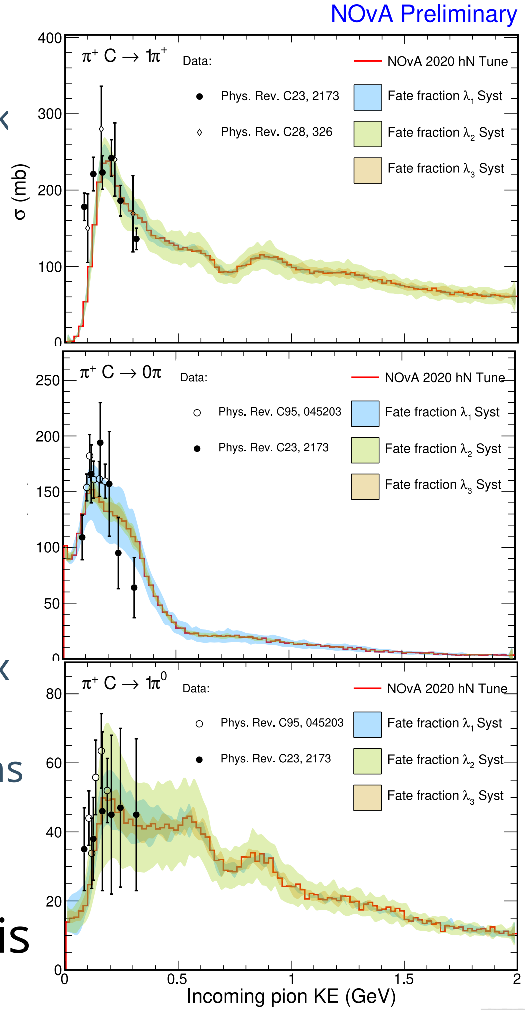
① It's straightforward to bracket the **mean free path** variations: f_{MFP}=0.4 and f_{MFP}=0.8

For the "**fate fractions**," we piggyback on analogous work done by T2K:

[adapted from PRD 99, 052007]



② We diagonalize the covariance matrix they obtain from fitting world data to obtain 3 independent ±1σ variations

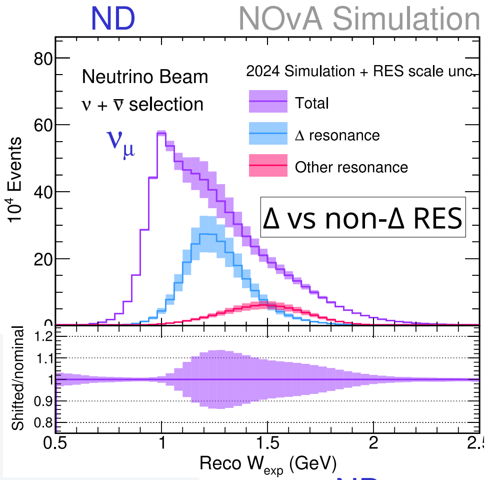


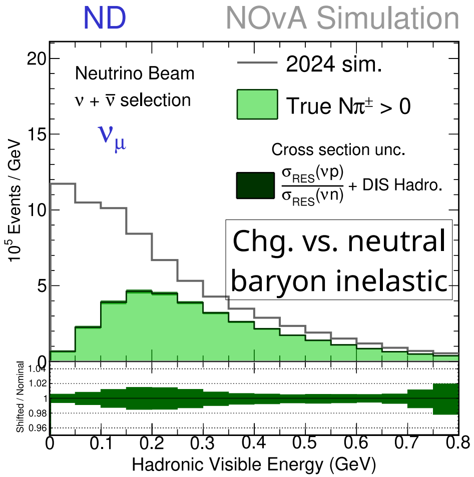
Use same "BDT reweight" technique as CV to implement in analysis

Pion production uncertainties

Two new categories of syst:

- Relative strength of Δ vs non-Δ resonant production (1 uncertainty)
  → Shift Δ and non-Δ resonances ±20% independently
  - Default GENIE: all resonances affected together
  - Overcounts Δ-specific uncertainty somewhat with other GENIE knobs, but "conservative"
- Charged vs. neutral baryon production in RES, DIS (2 uncertainties)
  - Shift ratio of RES Δ-channel proton/neutron final states by ±5%
  - Shift composition of proton/neutron final states in DIS
- Moderate impacts on pion-rich subsamples, but overall effect on uncertainty budget is minor





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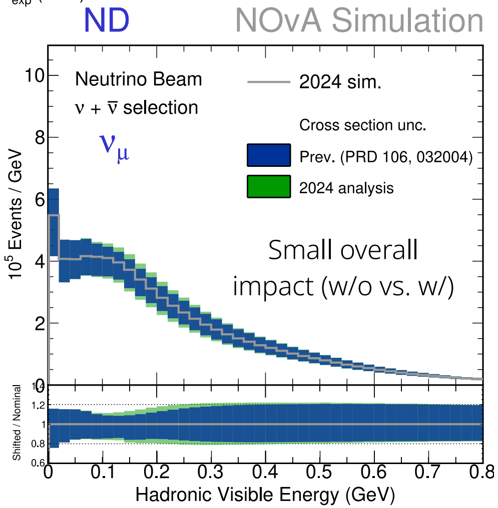
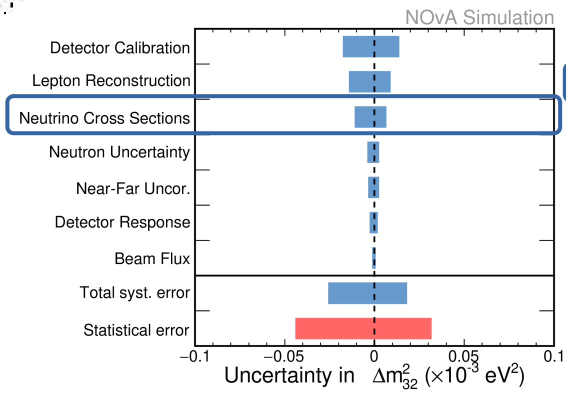
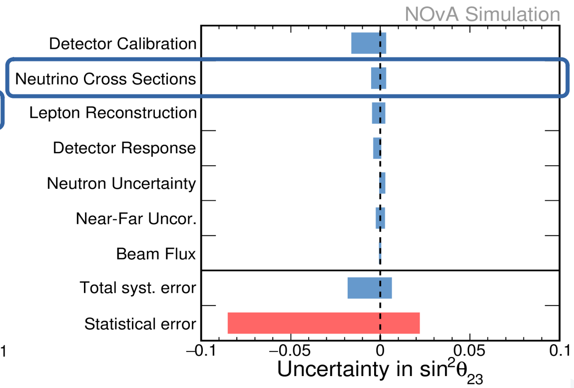


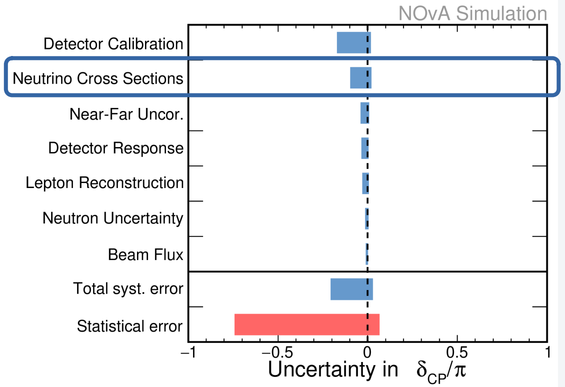
[see Neutrino '24 poster by M. Dolce & M. Martinez-Casales for more]

What matters the most?

What matters the most?







The **largest contributors** are not surprising:

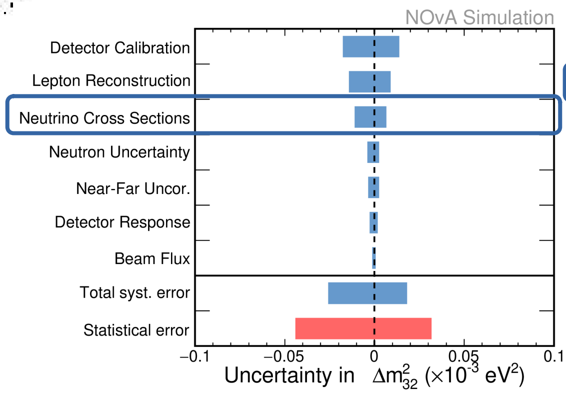
- CCQE z-expansion FF
- CCQE RPA
- CC RES M_A and M_V
- ν_e / ν_μ (unconstrained by ND)

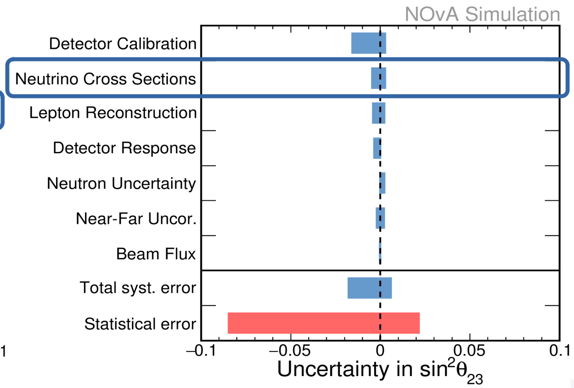
For **3-flavor oscillations** (and NSI),

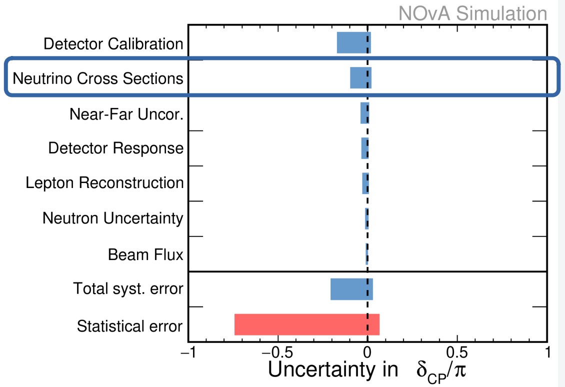
① **ν interaction uncertainties do not dominate**

(and we don't expect this to change even when data-taking is completed)

What matters the most?







The **largest contributors** are not surprising:

- CCQE z-expansion FF
- CCQE RPA
- CC RES M_A and M_V
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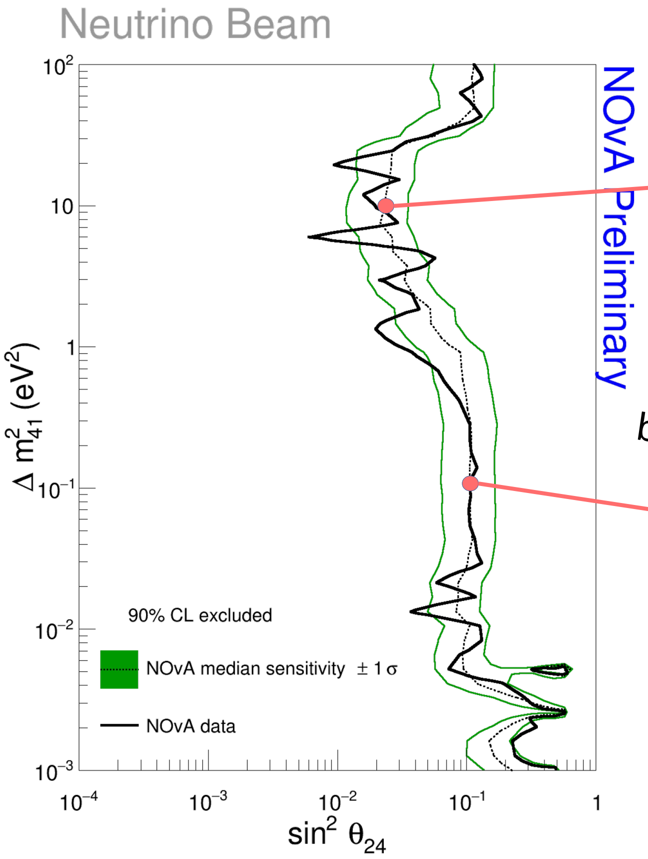
Recent theory work has concentrated on QE, but only ~20% of NOvA sample :(

For **3-flavor oscillations** (and NSI),

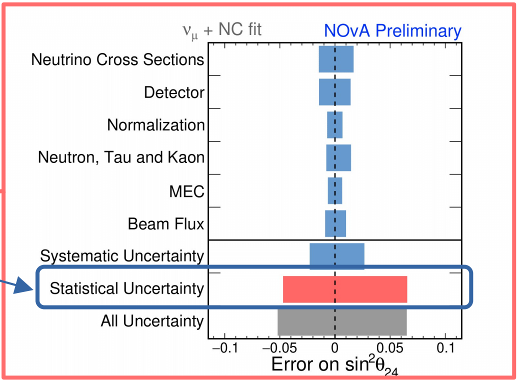
① **ν interaction uncertainties do not dominate**

(and we don't expect this to change even when data-taking is completed)

What matters the most?

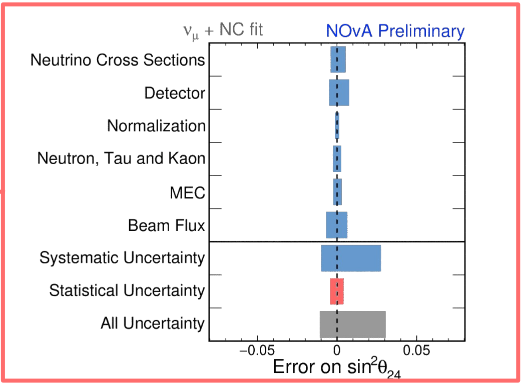


At high Δm², sensitivity driven by FD (low stats), thus stat. unc. dominates



At low Δm², sensitivity driven by ND (large stats), but syst. dependence is spread over many types of syst.

(+add **CCMEC, NC to significant xsec systs**)



② For **sterile ν searches**,
the situation is more interesting,
but **xsec systs still are not dominant**

What matters the most?

	ν_μ CC [PRD 107, 052011]	$\bar{\nu}_\mu$ CC [FNAL W&C seminar]	ν_e CC [PRL 130, 051802]	$\lvert q\rvert$-E_{avail} [arXiv:2410.05526]	Low E_{had} [FNAL W&C seminar]	ν_μ CC π^0 [PRD 107, 112008]
Flux	9.1	9.9	10.3	11.4	~11%	8.3
E-Scale + Det Model	6.1	6.1	8.6	3.8	~5-6%	7.6
Cross Section Model	1.9	2.5	9.8	5.6	~2%	4.6
Neutron Modeling	1.5	2.3			~3%	
Statistical			7.4			
2p2h Model				7.1		
Pi Charge Exchange						3.8

Predominantly ν_μ CC π^0 channels (major bkgd) and ν_e MEC (in signal; not called out separately)

Observables deliberately in hadronic system, thus inevitable

FSI is major production mechanism for π^0

③ For **neutrino scattering** measurements, **xsec systs** are sometimes important, but *which* **depends a lot on the channel**

Future directions

2-detector fitting

FERMILAB-THESIS-2023-08

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
in
Physics
Tufts University

August 2023
Adviser: Prof. Hugh Gallagher

[M. Dolce, Tufts Univ., 2023]

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

Major: High Energy Physics

Program of Study Committee:
Mayly Sanchez, Co-major Professor
Matthew Wetstein, Co-major Professor
Rebecca Flint
Soeren A. Prell
Kirill Tuchin
Amanda Weinstein

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Iowa State University
Ames, Iowa
2023
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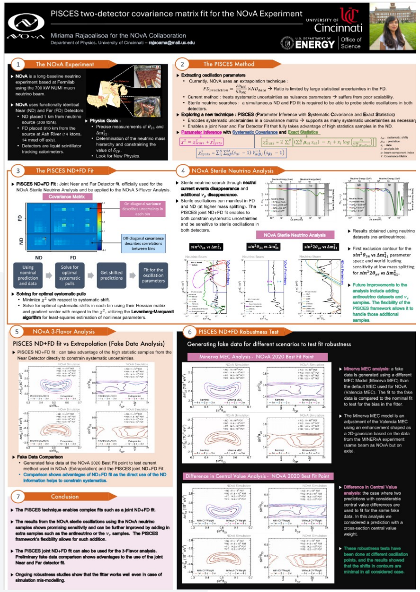
[M. Martinez Casales, Iowa State U., 2023]



[M. Rajaoalisoa, Neutrino '24 poster]

Not being able to depend on “extrapolation” forcing us to grapple with **need for more exhaustive ν int systematics**

- Extending work begun for sterile ν search & xsec measurements (model spread MEC)
- New π-production systs emerged from this work

Strong collaboration interest in **exploring simultaneous 2-det fits** in lieu of “extrapolation” for 3-flavor oscillations

GENIE "AR23" and 'nusystematics'

- Recent flurry of effort from DUNE/SBN to produce models usable in multiple expt contexts
  - GENIE configuration AR23_20i_00_000 encapsulates base model choices
  - nusystematics contains publicly-accessible cross section uncertainty knobs (like NOvARwgt)
- We are seriously exploring leveraging this effort for our last major simulation production campaign
  - Base model has desirable flexibility for *post hoc* reweighting
  - Many systematics are in same spirit as, but more sophisticated than, our custom knobs
- Some technical hurdles to overcome
  - Legacy choices about MC format & persistence from 10+ years ago make this … creaky, but doable with effort

Summary thoughts

NOvA experience with xsec systs

- "Functionally equivalent" detector design & "extrapolation" paradigm a powerful combination
  - Blunted impact of intrigue over 1p1h & 2p2h
  - Enabled *staged* improvements to the model with limited personnel
  - Even at full exposure don't anticipate xsec systs limiting 3-flavor results
- "Owning" complete xsec model requires critical mass of interested generator experts
  - Our targeted "bespoke" uncertainties approach only possible against the larger backdrop of centralized GENIE library
  - We have profited extensively from cross-collaboration … collaboration (MINERvA, T2K, DUNE)
- Effort required to convert non-reweightable to reweightable worth the investment
  - Expanded usable model space in regions important to NOvA (π FSI, hadronization)
  - Interesting intellectual / technical challenge, fun for students / postdocs

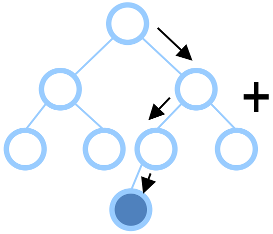
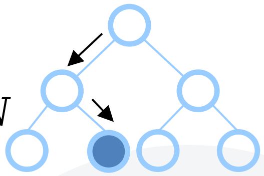
Lessons for future experiments

- Experiment & analysis design sculpt uncertainty needs
  - Different weaknesses of global cross section picture are thrown into relief at 600 MeV vs. 2 GeV vs. 5+ GeV
  - “Extrapolation” vs. “simultaneous 2-detector fit” (vs. PRISM!) impose different demands on model
- Real data is a blessing and a curse
  - Don’t always have the luxury of fully rigorous model-based uncertainties
  - Judicious “blends” of model- and data-based uncertainties can be effective stand-ins when all else fails
- Technical model synergy with the wider community is extremely profitable, but requires some “homework”
  - Choices made in early stages of persistence & large-scale simulation infrastructure can later become obstacles

Overflow slides follow

BDT reweights

We use a boosted decision tree technique....

$f_{BDT} = \alpha_1$  $+ \; \dots \; + \; \alpha_N$ 

$$\simeq \frac{1}{N} \sum_{i=1}^{N_{tree}} \alpha_i \Theta\left(\vec{x} - \vec{x}_0^{\,i}\right)$$

event values

trained "cut" for tree *i*

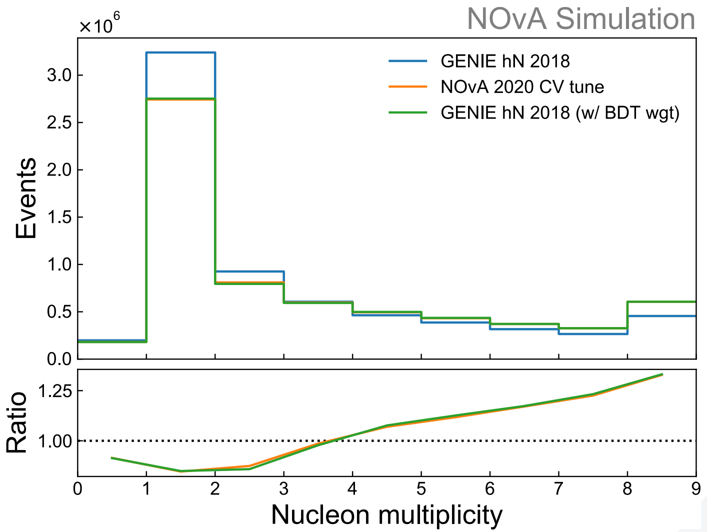
BDT trained using binary logistic loss to distinguish between simulated GENIE CV and desired "alternate" sample

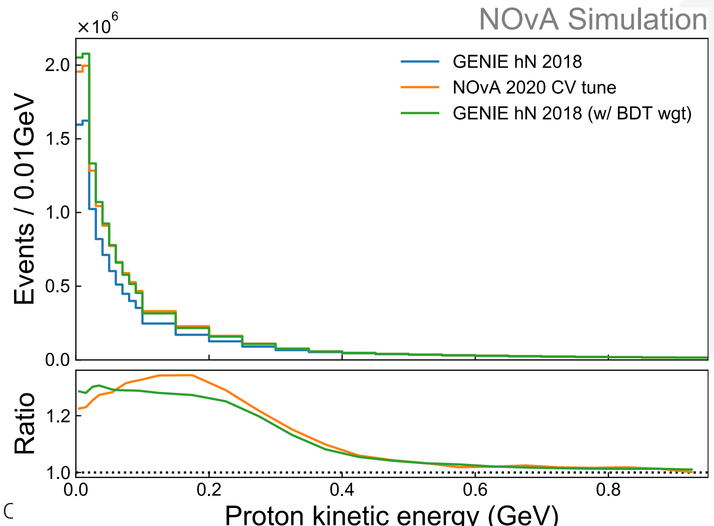
... to create reweights from the nominal to the uncertainty samples

$$w(\vec{x}) = \frac{f_{BDT}(\vec{x})}{1 - f_{BDT}(\vec{x})}$$

(detailed discussion of technique in NuSTEC CTGWG Seminar Dec. 14, 2022)

BDT reweights





While not perfect, performance is adequate to use as a computing time-saver