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NOvA central value tuning and uncertainties for the hN FSI model in GENIE 3

for the NOvA Collaboration

Jeremy Wolcott

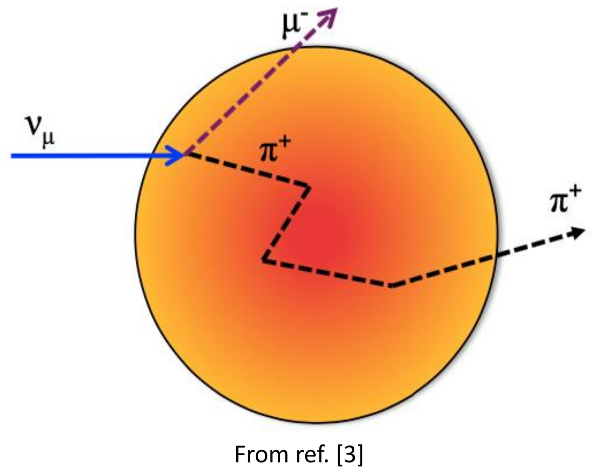
Michael Dolce

Hugh Gallagher

Tufts UNIVERSITY

1) Background

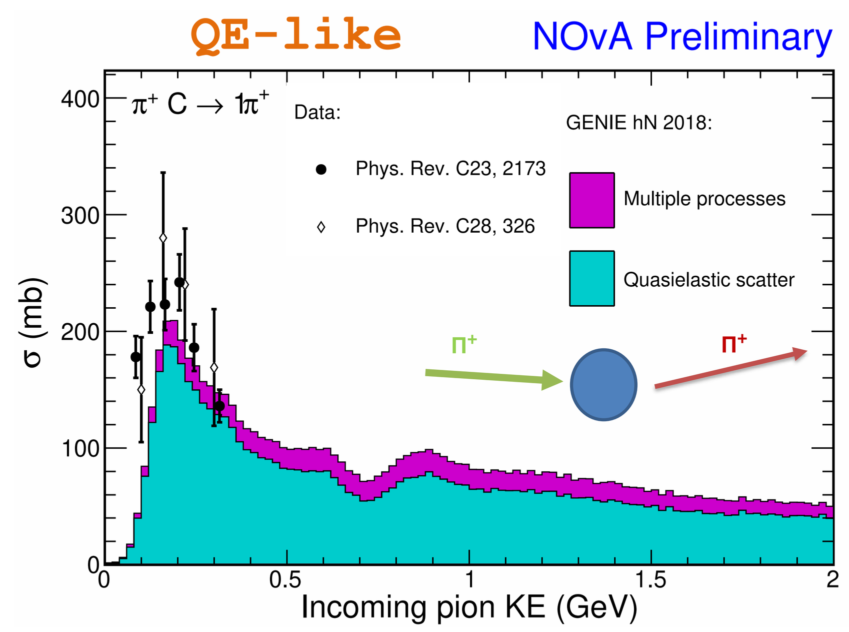
Hadrons produced from a neutrino scattering interaction can re-interact within the nucleus as it is traversed. These re-interactions are known as final state interactions (FSI).

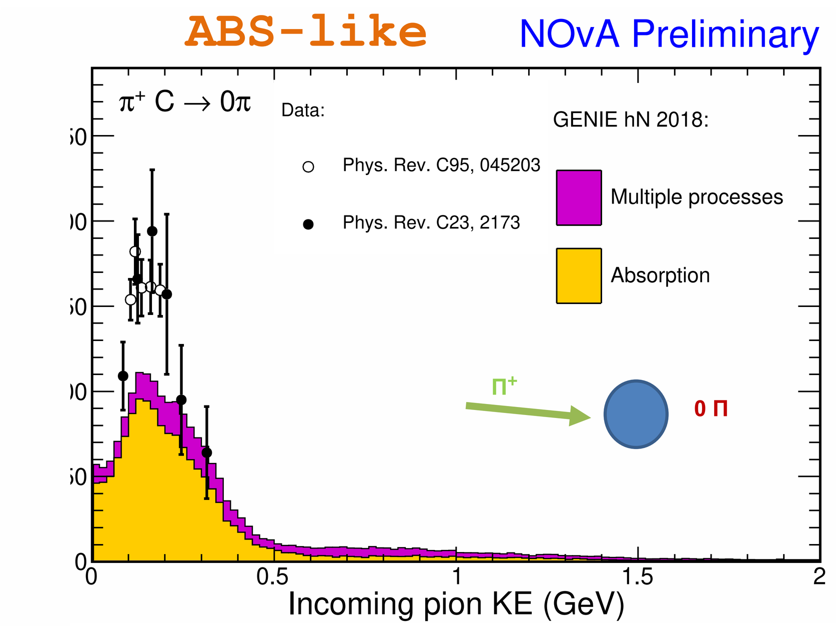


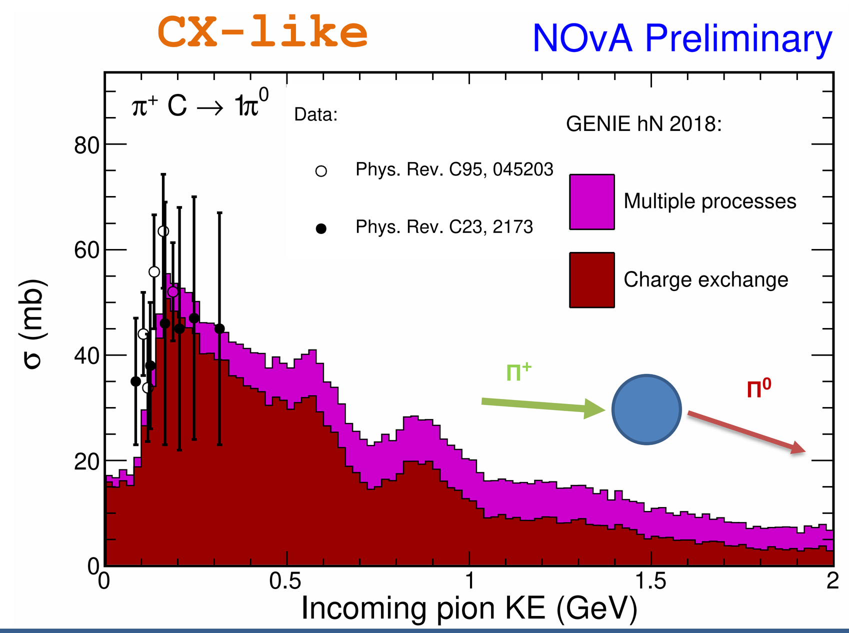
From ref. [3]

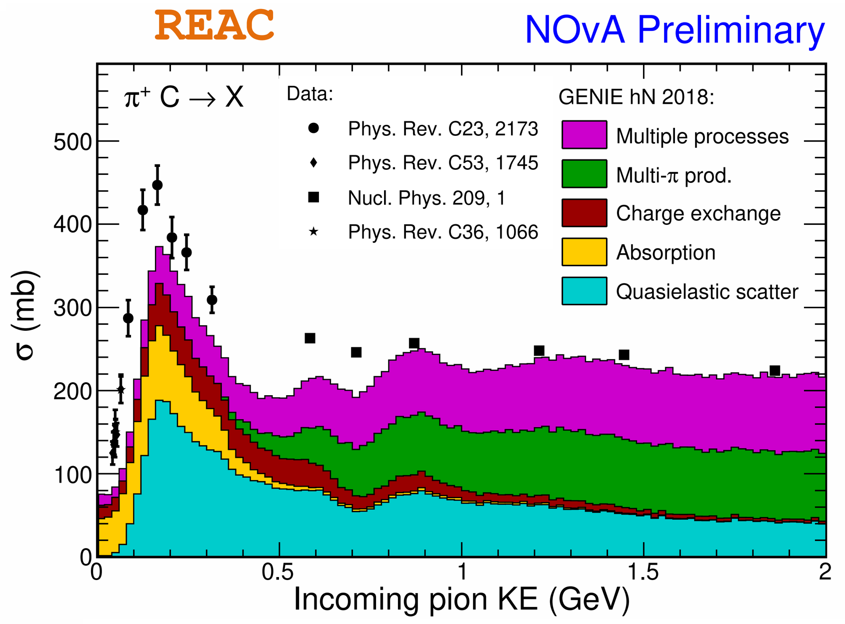
For 2020 NOvA chose to use the hN2018 semi-classical cascade FSI model in GENIE 3.0.6 [1] because, as opposed to the "effective" model hA, hN uses an explicit model [2] to predict how external pion scattering data is connected to propagation inside the nucleus.

2) Final State Interactions Classifications in GENIE 3







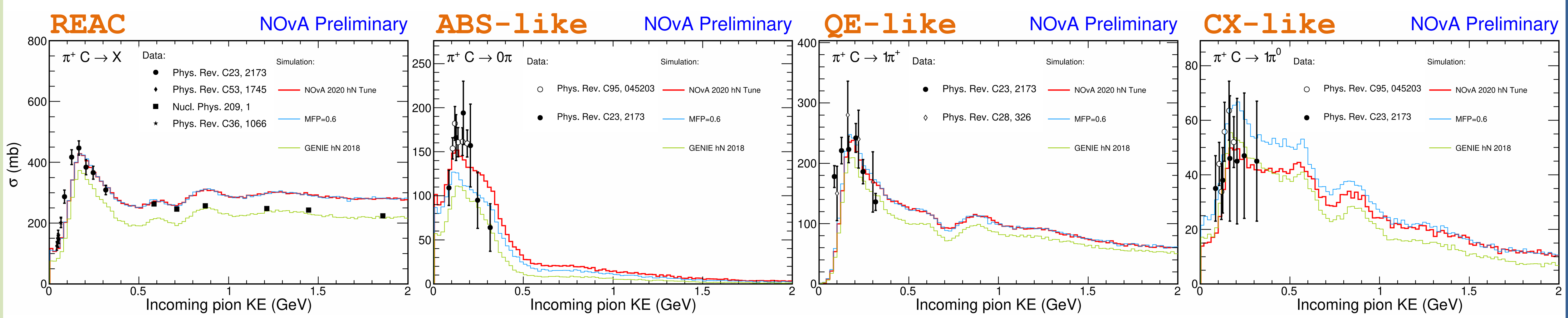


$\pi^+ - {}^{12}C$ scattering data may be grouped into three topological categories based on outgoing particles: QE-like, CX-like, and ABS-like. By combining all categories together, we obtain the total reactive cross section (REAC).

Agreement between hN2018 and extant data on ${}^{12}C$ is poor – particularly for ABS-like and REAC – motivating us to tune GENIE's prediction.

We do so by adjusting the "fate fractions" that dictate the probability of a true QE, ABS, or CX interaction in the generator.

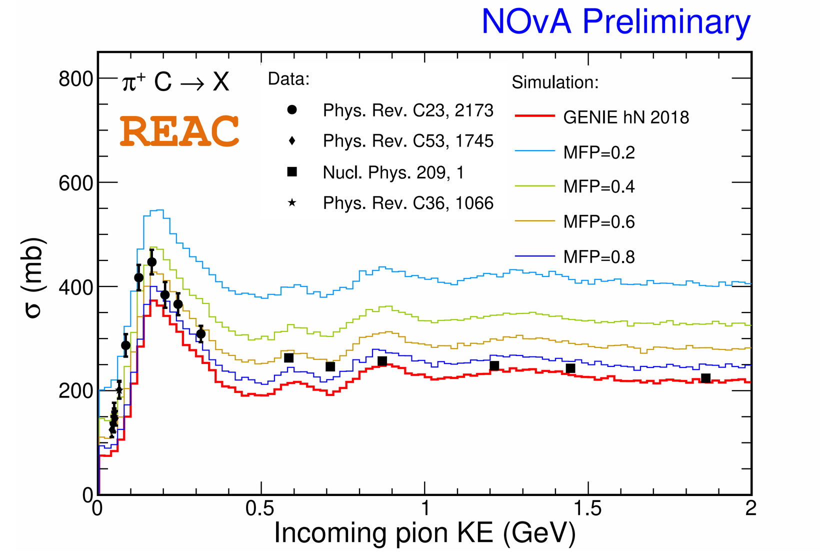
3) Central Value Tuning



We scale the hN2018 Mean Free Path (MFP), which scales inversely with cross section, to make the prediction agree with total reaction cross section data (REAC).
We then tune the fate fractions for the individual true processes' probabilities, ensuring we conserve total probability at unity, using individual channel data.

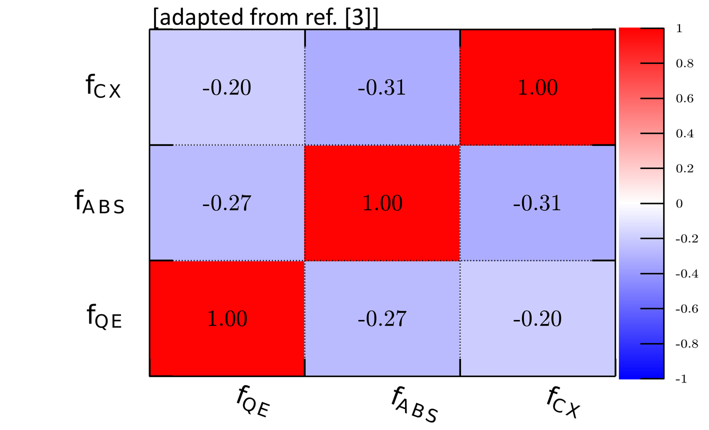
Parameter	Description	value
f_{MFP}	Mean Free Path	0.6
f_{ABS}	Absorption	1.4
f_{CX}	Charge Exchange	0.7
f_{QE}	Quasi-elastic	0.9

4) Constructing Uncertainties

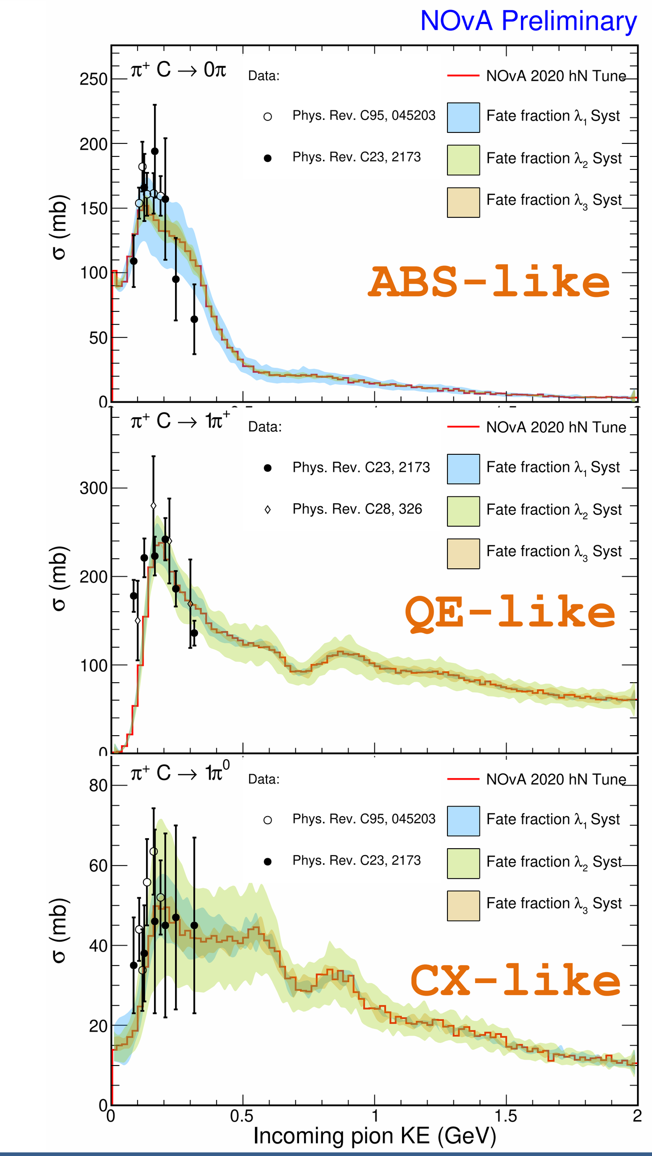


We scan MFP variations to select values that bracket the data: 0.4 and 0.8 (CV=0.6).

We diagonalize the covariance matrix in the fate fractions from similar work by T2K [3] to obtain three linearly independent error variations (below).

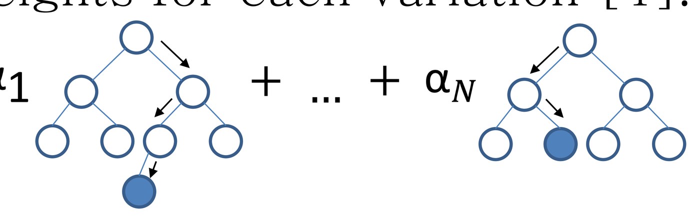


Knob	shift (σ)	f_{MFP}	f_{ABS}	f_{CX}	f_{QE}
Fate fraction #1	+1	0.6	0.9	0.8	1.0
	-1	0.6	1.8	0.6	0.8
Fate fraction #2	+1	0.6	1.4	0.9	0.7
	-1	0.6	1.4	0.5	1.2
Fate fraction #3	+1	0.6	1.3	0.5	0.8
	-1	0.6	1.4	0.9	1.0
Mean free path	+1	0.8	1.4	0.7	0.9
	-1	0.4	1.4	0.7	0.9



5) Boosted Decision Trees (BDTs)

To avoid having to fully resimulate ν scattering to apply tunes, we train BDTs using truth quantities to build reweights for each variation [4].

$f_{BDT} = \alpha_1$  $+ \ldots + \alpha_N$

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

, with $\vec{x}$ = (# hadrons, hadron KE, …)

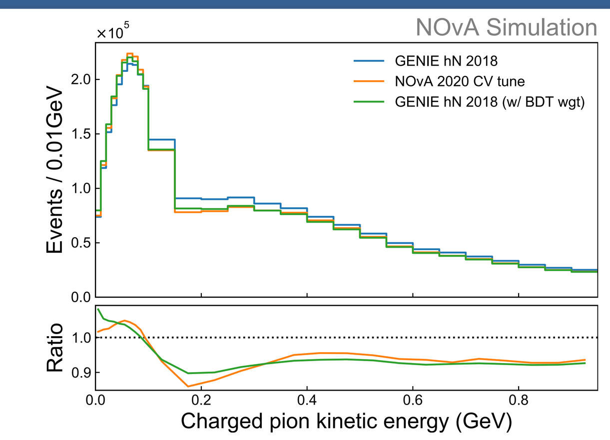
($\vec{x}$: event values; $\vec{x}_0^{\,i}$: trained "cut" for tree i)

We use a binary logistic loss as the training objective:

$$L_{\log} = \sum_{\text{training evt } n} -y_n \ln \hat{y}_n + (y_n - 1)\ln(1 - \hat{y}_n)$$

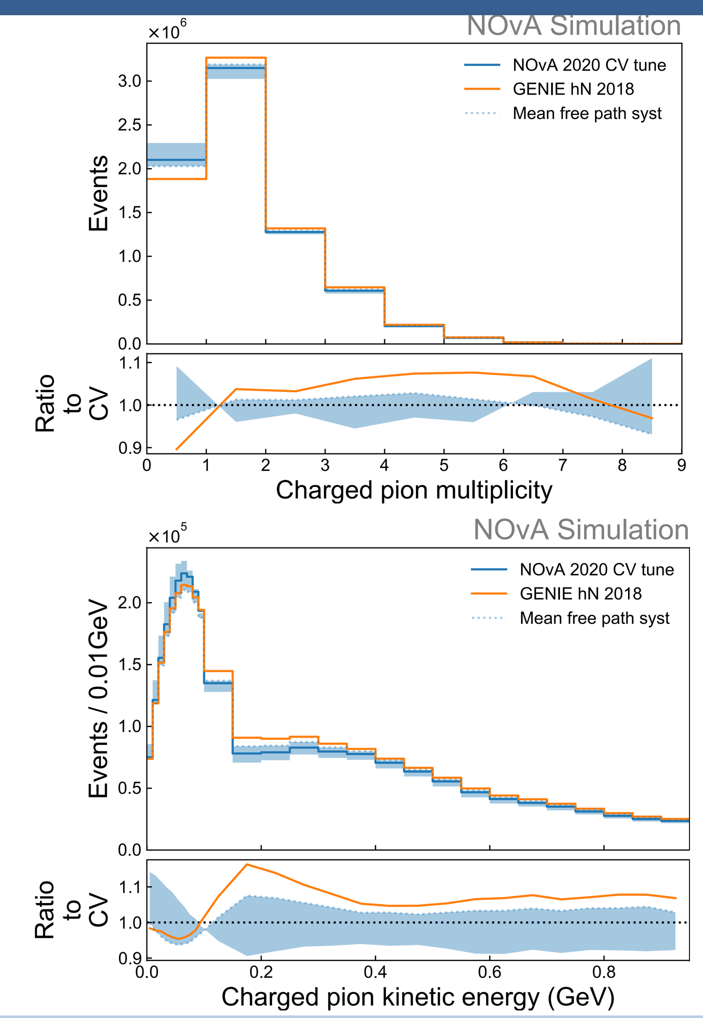
The desired weights for an event $\vec{x}$ are:

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



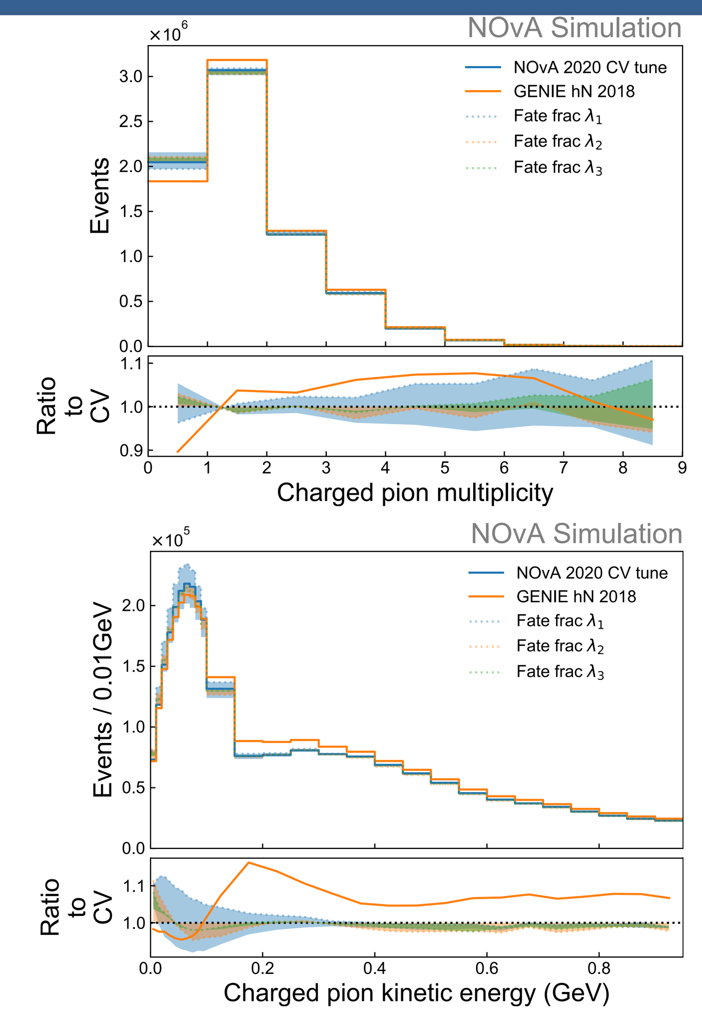
The variations are well reproduced by applying the $w(\vec{x})$ to nominal hN2018 simulation.

6) Impact on Neutrino Predictions



In a generated neutrino sample, the resulting uncertainties create 5–10% variations in true pion observables in neutrino reactions.

We use these variations as systematic uncertainties in the NOvA oscillation analysis.



http://novaexperiment.fnal.gov

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References

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3. E.S. Pinzon Guerra et al. *Phys Rev.* D**99**: 052007 (2019).
4. A. Rogozhnikov. *J. Phys. Conf. Ser.* **762**: 012036 (2016).