FERMILAB-SLIDES-20-070-LBNF

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

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New Perspectives — July 21, 2020

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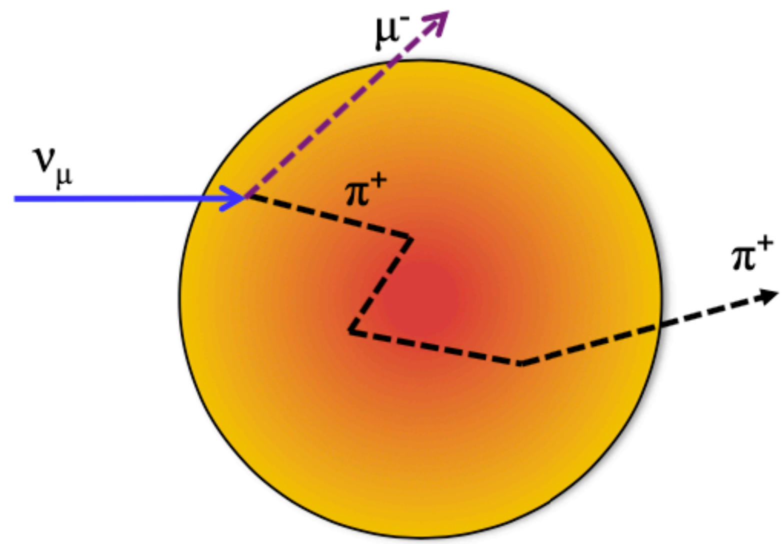
Final State Interactions

What is FSI and why is it important?

- In a neutrino interaction, hadrons are produced inside the nucleus.
- While traversing the nucleus, hadrons can re-interact, known as Final State Interactions (FSI).
- FSI's impact on neutrino scattering is significant:

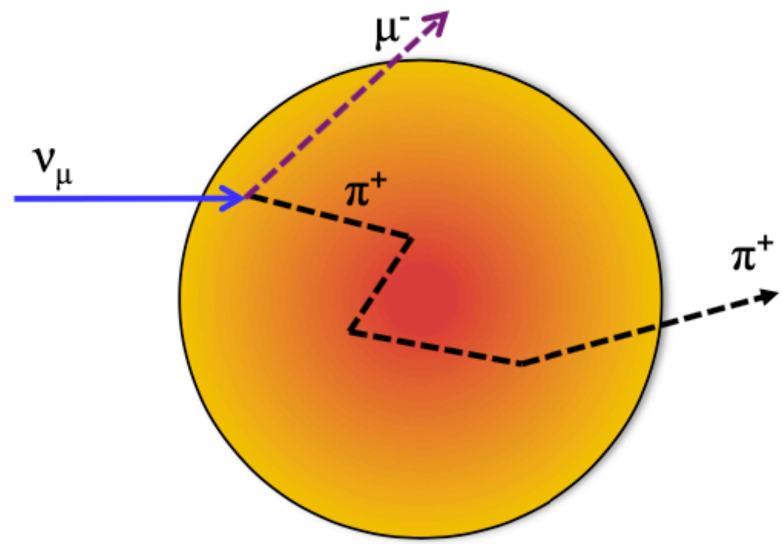


Ref [3]

Final State Interactions

What is FSI and why is it important?

- In a neutrino interaction, hadrons are produced inside the nucleus.
- While traversing the nucleus, hadrons can re-interact, known as Final State Interactions (FSI).
- FSI's impact on neutrino scattering is significant:
    - Observed final state products may not have been what was created in the neutrino interaction.
    - For example, a pion produced might have experienced multiple scatters, where it could gain or lose significant energy, before it ultimately exists the nucleus.
        - Effects like these can impact your neutrino energy reconstruction!



Ref [3]

Final State Interactions
What are the FSI models?

- The NOvA collaboration uses the neutrino generator GENIE [1].
- In the latest GENIE version, 3.0.6, there are two FSI models.

"Effective" cascade model, hA:

- Predictions are derived directly from hadron scattering data.
    - No attempt is made to differentiate between free hadron scattering and intranuclear interactions.
- This is the historical FSI model in GENIE.

Semi-classical cascade model, hN:

- Probability of hadronic interaction is calculated in discrete steps through a nuclear density model.
    - An interaction can occur at any of these steps.
- Interactions are predicted from a model [2] that relates pion scattering data to intranuclear amplitudes.

Final State Interactions

Understanding the context for our study

- NOvA selects the hN model for two reasons:
    1. More theoretically grounded approach.
    2. A level of synergy for the joint NOvA-T2K analysis (T2K uses an analogous hN model).

- hN uses an explicit model [2] to translate an intrauclear pion to an amplitude from pion scattering data.
    - By generating π^{+}—^{12}C in GENIE, we can make comparisons to available data to demonstrate the accuracy of the hN FSI model.

Comparing Pion Scattering Simulation & Data

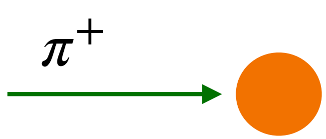
Pion Scattering Simulation & Data

Categorizing pion scattering data

- Generally, external pion scattering data is categorized into three topological channels:

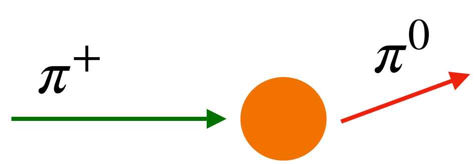
Absorption (ABS)

No pions are observed in the final state.



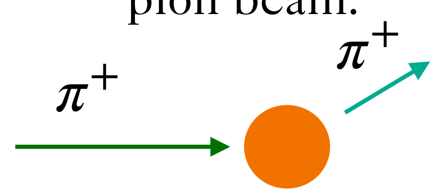
Charge Exchange (CX)

a single π^0 is observed in the final state.



Quasi-Elastic (QE)

Single pion is observed, with same sign as initial pion beam.



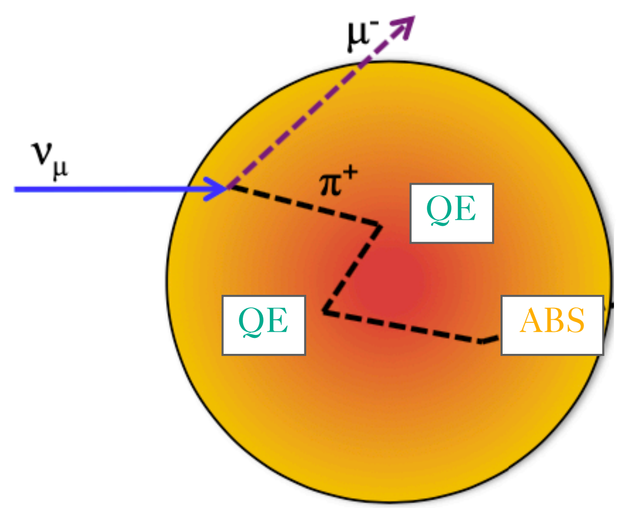
- We can sum these channels together, REAC = ABS + CX + QE + (other processes).
  - This is the total "reactive" cross section.
  - We will utilize REAC for our tuning needs too.

Pion Scattering Simulation & Data

How to use pion scattering sim. & data for FSI

- In FSI, truth processes can occur at each step of propagation.
- A pion might QE scatter first, and then later experience ABS (right).
    - In our study, we classify this as "Multiple processes", (in this case under topological ABS).
- The result is truth channels do not correspond "1-1" to the topological processes.

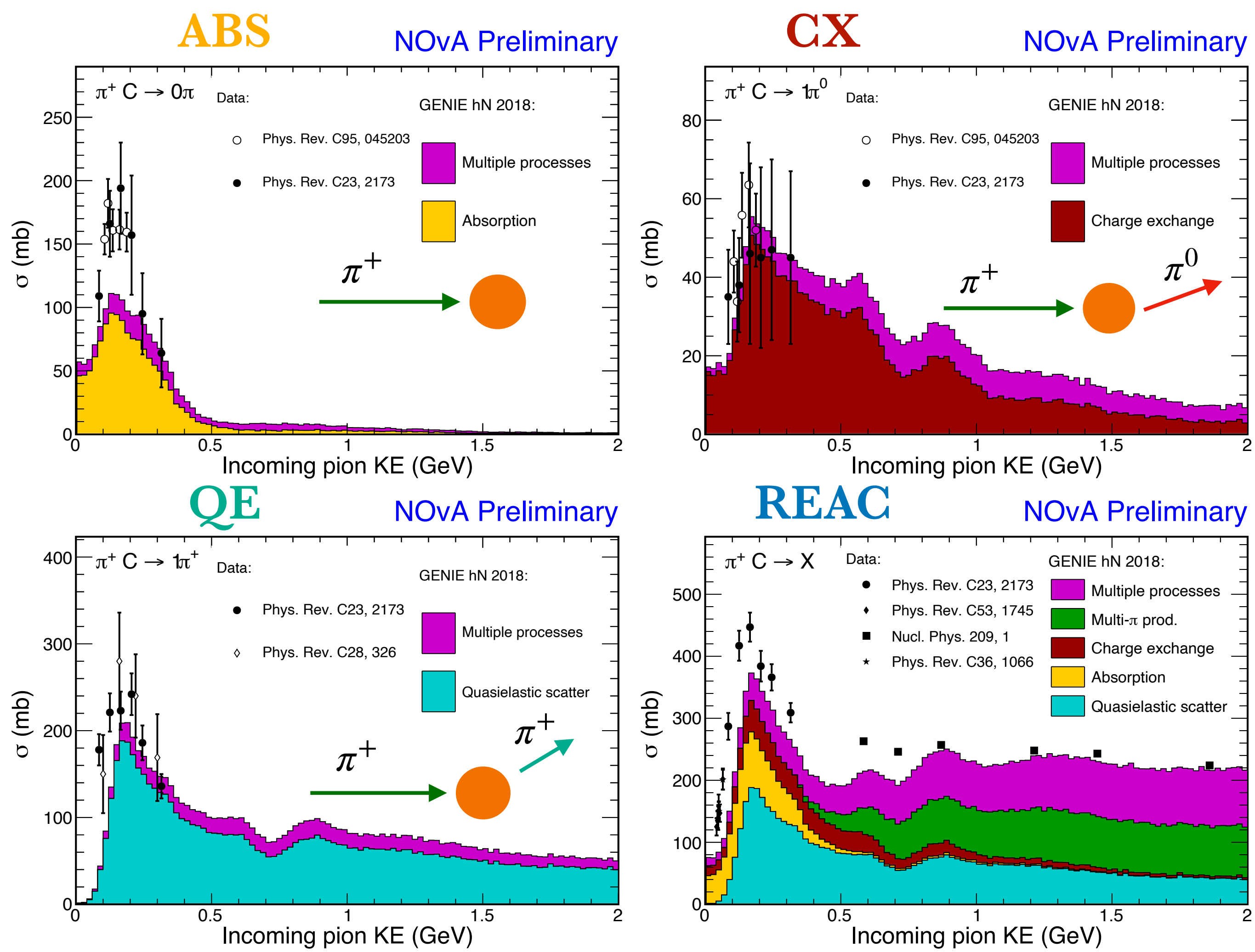
- From GENIE, we include these "Multiple processes" and categorize all simulation into the data-driven topological channels (ABS, CX, QE) to evaluate the hN model.



Adapted from [3]

Pion Scattering Simulation & Data

How does nominal hN compare to pion data?

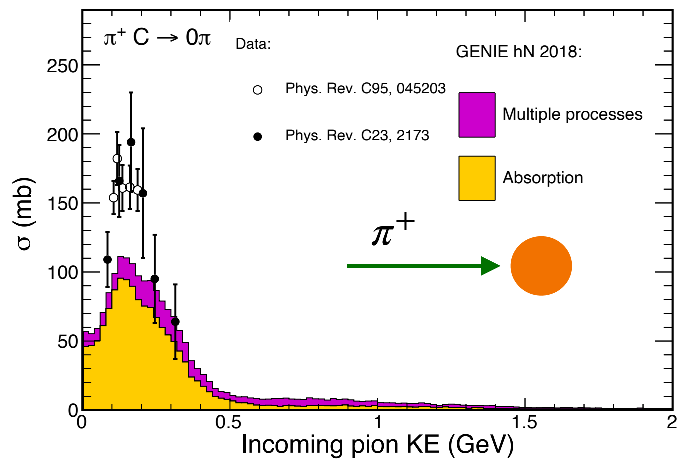


Pion Scattering Simulation & Data

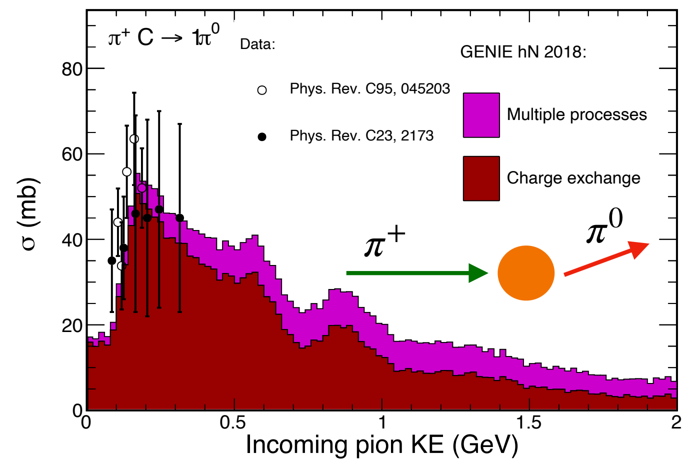
How does nominal hN compare to pion data?

- hN tuning is required — agreement to data is poor in ABS and REAC channels.

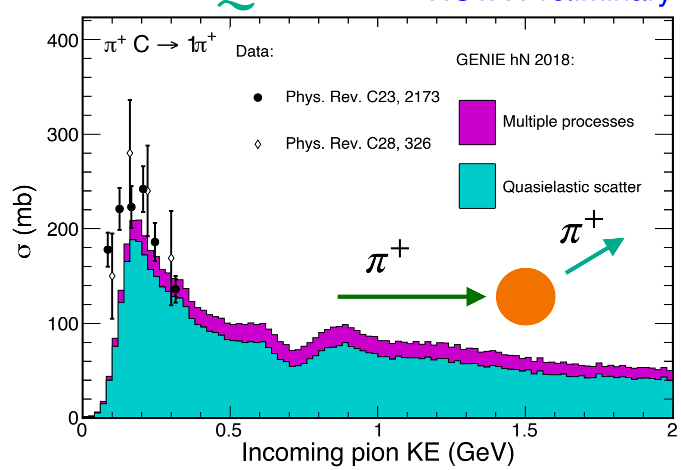
ABS NOvA Preliminary



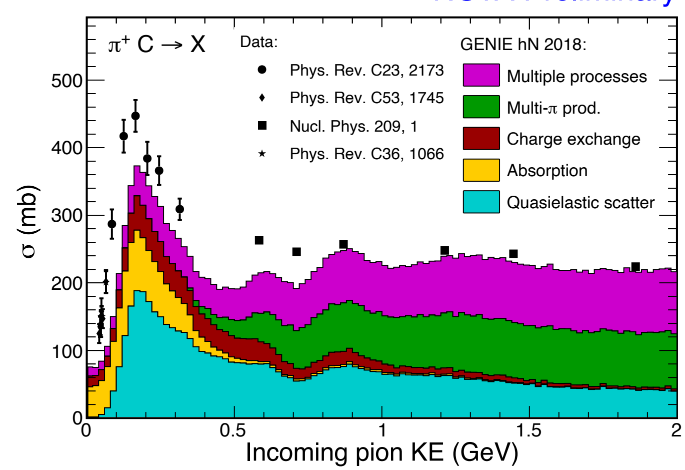
CX NOvA Preliminary



QE NOvA Preliminary



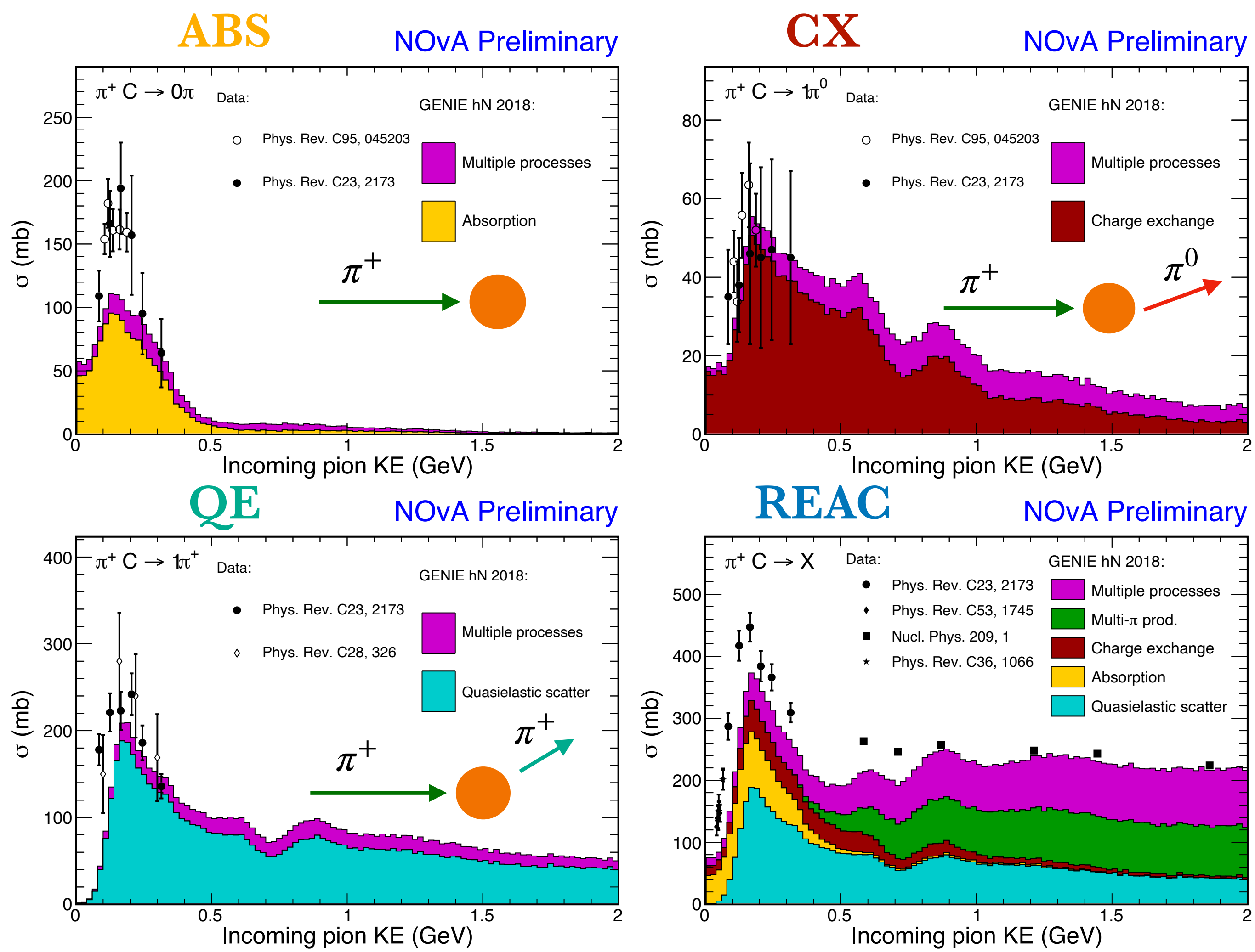
REAC NOvA Preliminary



Pion Scattering Simulation & Data

How does nominal hN compare to pion data?

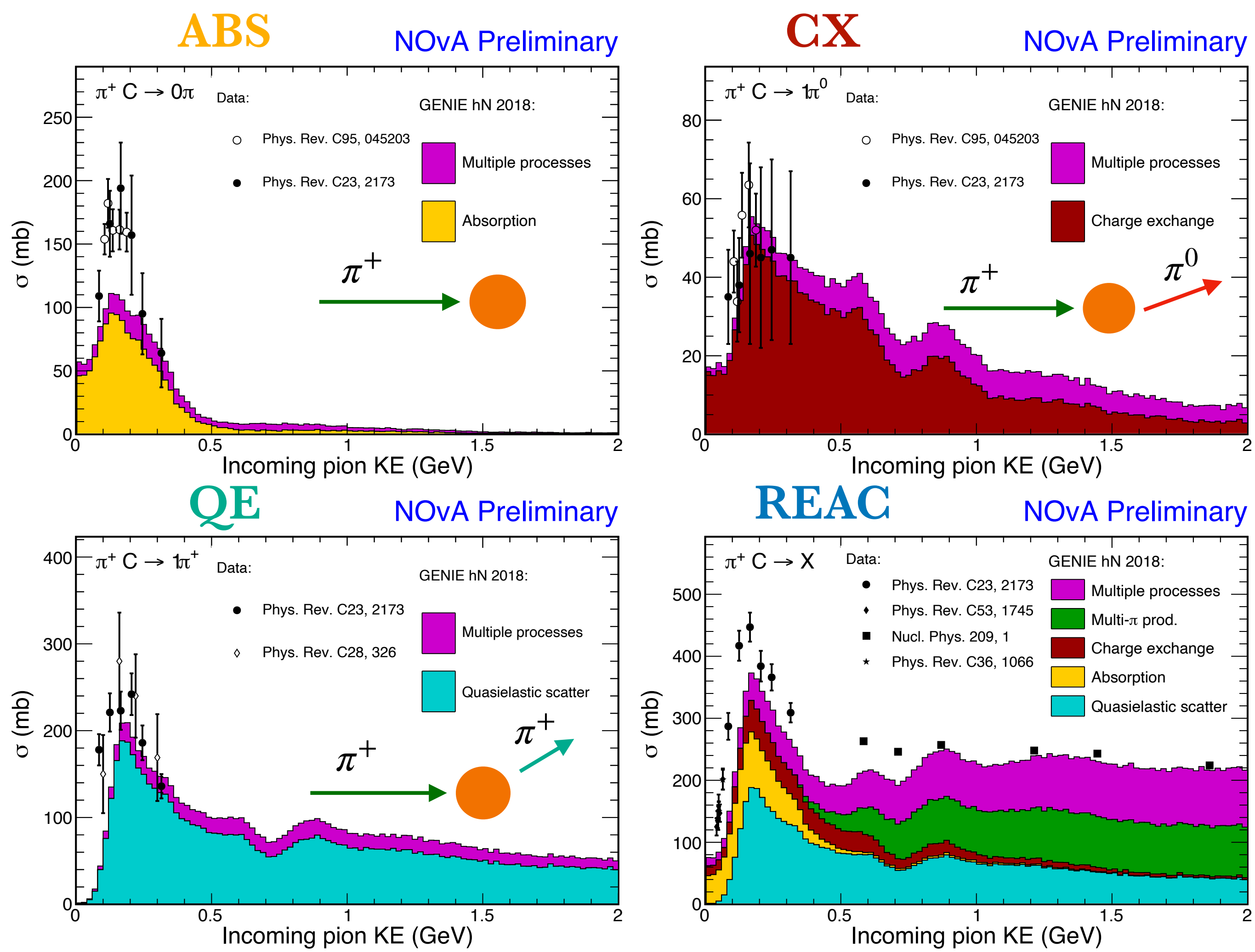
- hN tuning is required — agreement to data is poor in ABS and REAC channels.
- For REAC, tuning of the total reactive cross section is required.



Pion Scattering Simulation & Data

How does nominal hN compare to pion data?

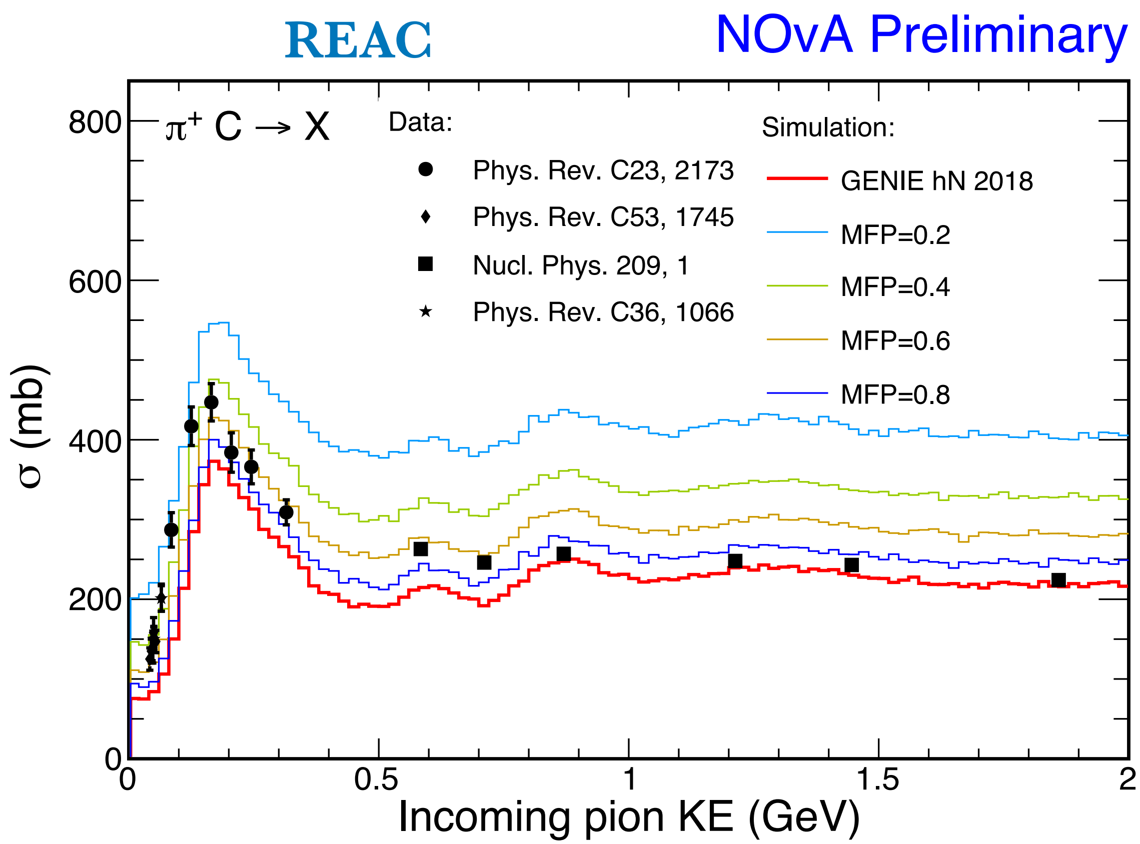
- hN tuning is required — agreement to data is poor in ABS and REAC channels.
- For REAC, tuning of the total reactive cross section is required.
- For the topological channels, we tune the relative probability for each truth process (fABS, fCX, fQE).



Central Value Tuning

Tuning the reactive cross section

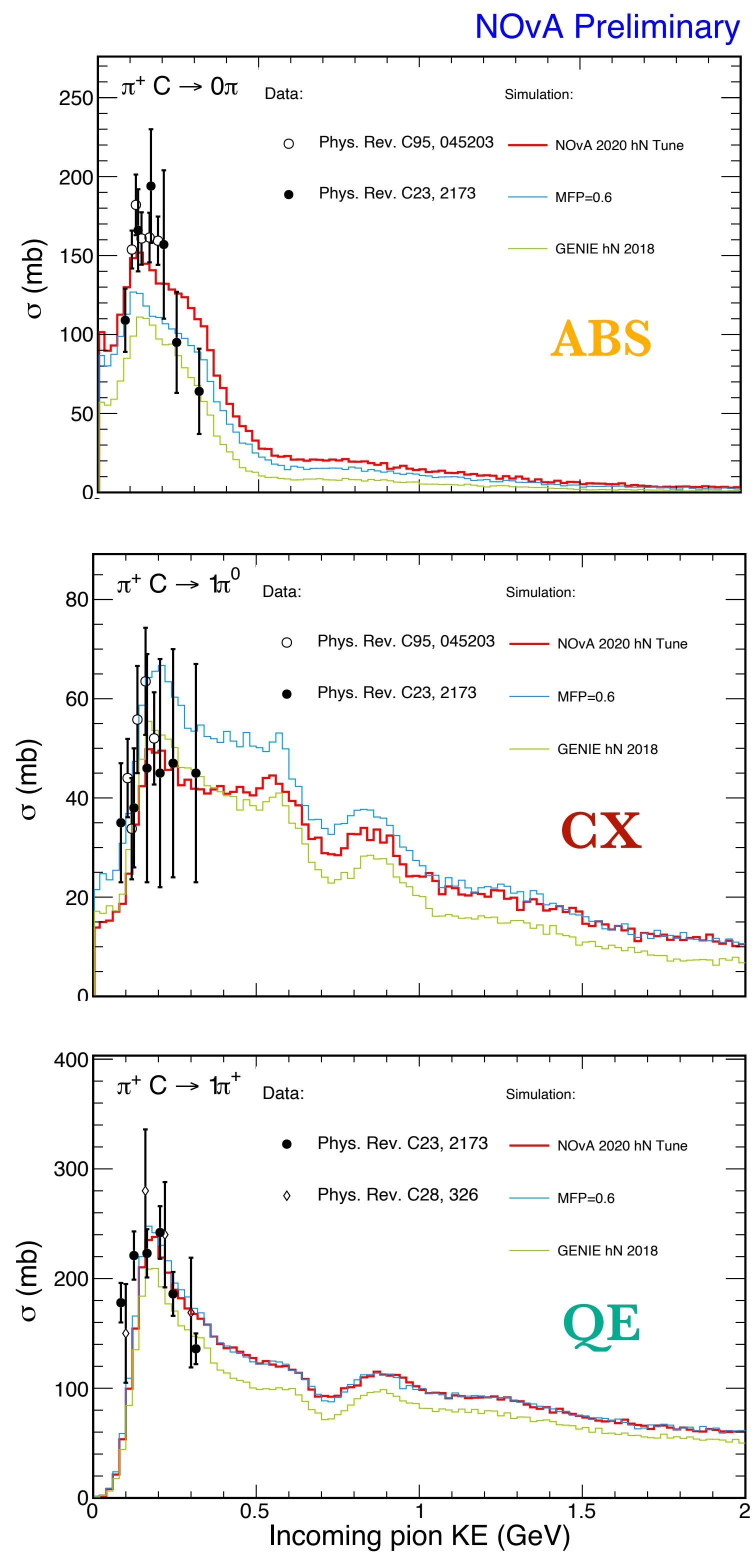
- We start with REAC (i.e., the total "reactive" cross section).
- We reduce the Mean Free Path (MFP), which scales inversely with cross section.
- We scan MFP values and select 60% the nominal value.
  - This provides the best agreement in the $KE_\pi < 500$ MeV region.
- Note: MFP reduction will increase the cross section for ABS, CX, & QE as well.



Central Value Tuning

Tuning the truth processes

- Next we tune the GENIE truth channels.
- Again, note the increase in cross section for each channel from MFP reduction.
- We tune the relative probabilities while conserving the total probability:
  - We increase fABS by 40% and reduce fQE and fCX to maintain total probability.
    - We see improved agreement in ABS.
    - The CX prediction is reduced.



Central Value Tuning

Our CV

- The following is the result of our tuning procedure:
    - 40% increase in fABS.
    - 30% reduction in fCX.
    - 10% reduction in fQE.
    - 40% reduction in MFP.
- This is our Central Value (CV).
- Next, is to build uncertainties…

Process	Parameter	Value
Absorption	fABS	1.4
Charge Exchange	fCX	0.7
Quasi-Elastic	fQE	0.9
REAC	MFP	0.6

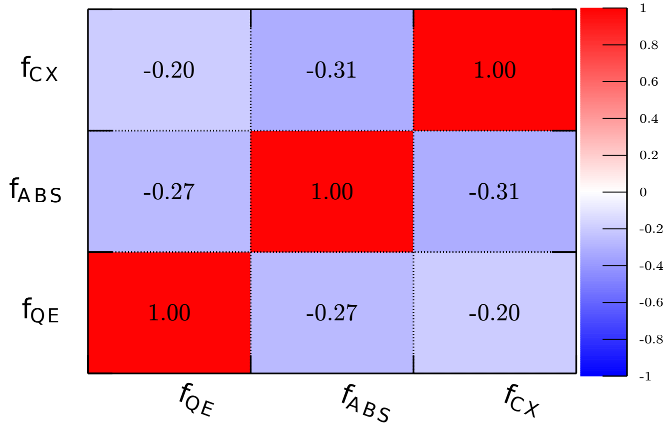
Constructing Uncertainties

Constructing Uncertainties

Creating uncorrelated errors

- We would like to create uncorrelated uncertainties so to treat each one as an independent knob for our oscillation fit.
- T2K has performed a similar study with an analogous hN model.
- As we use similar models, our CV parameters (fABS, fCX, fQE) are also similar.
    - Allows us to adapt T2K's correlation matrix (right) for our CV parameters.

- We construct a covariance matrix, diagonalize it, and obtain eigenvalues and eigenvectors.
    - Provides three sets of uncorrelated error variations for our three parameters.

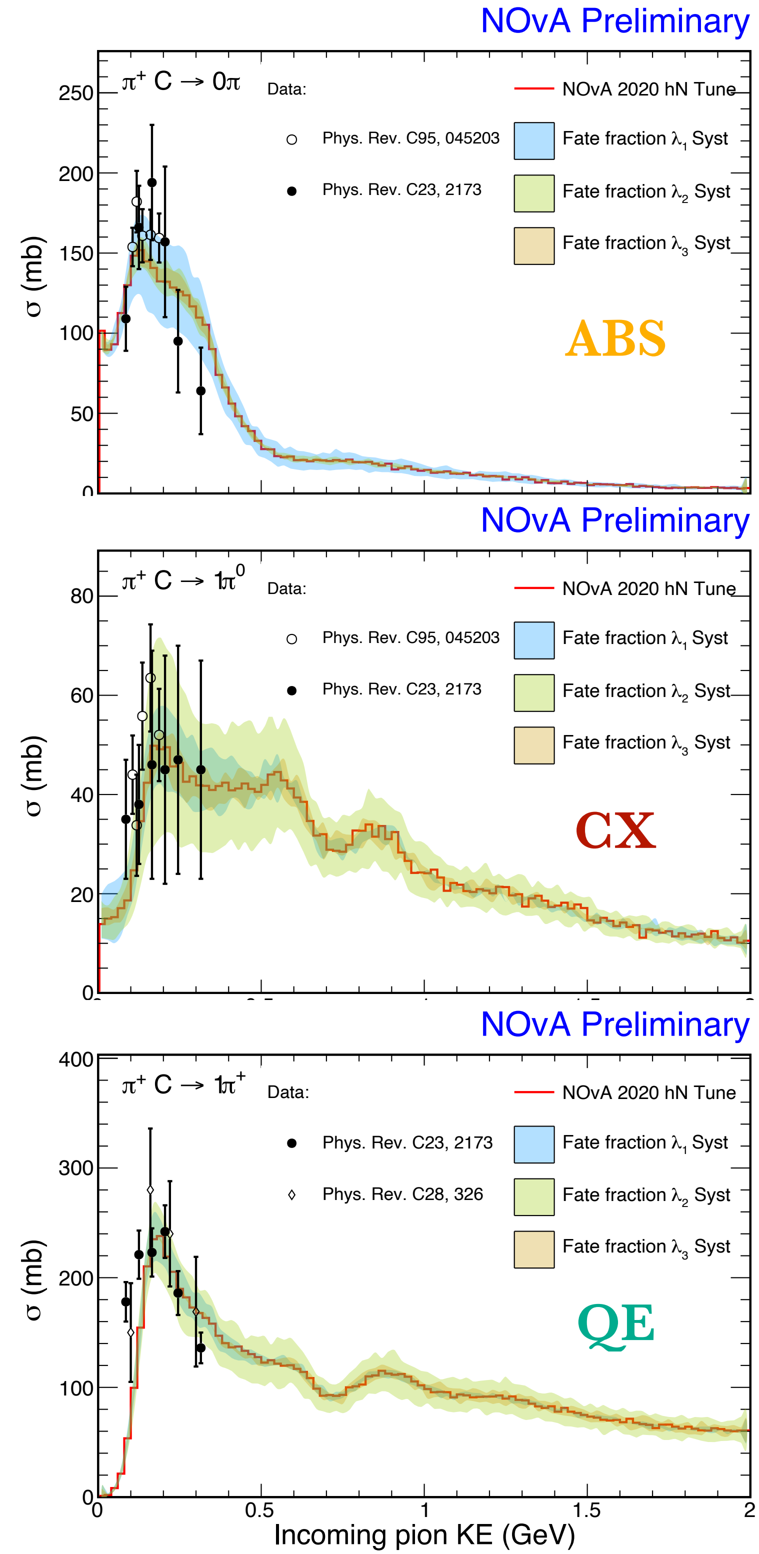


Adapted from [3]

Constructing Uncertainties

Error variations for truth processes

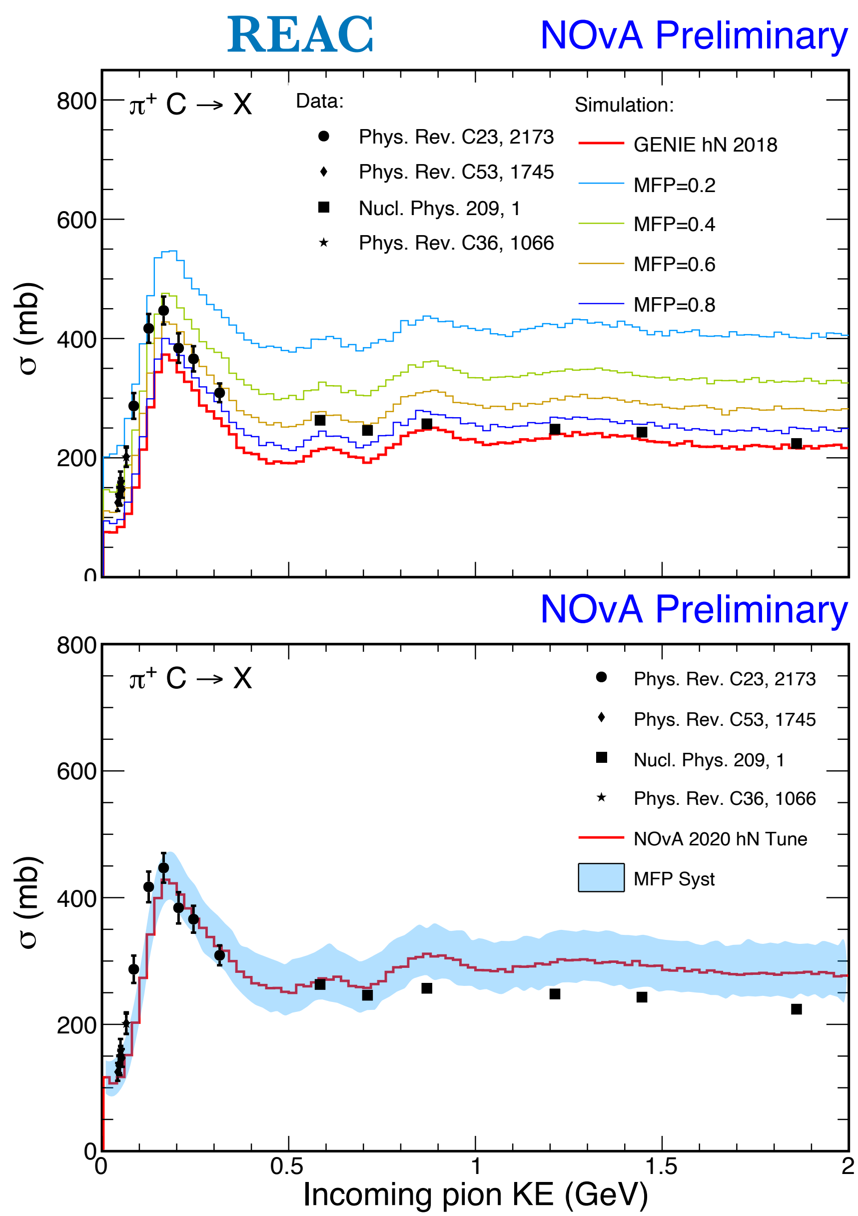
- Each colored error band is one set of uncorrelated uncertainties.
- For our neutrino analysis, each colored-band will be treated as an independent knob for our oscillation fit.



Constructing Uncertainties

Error variation for the MFP

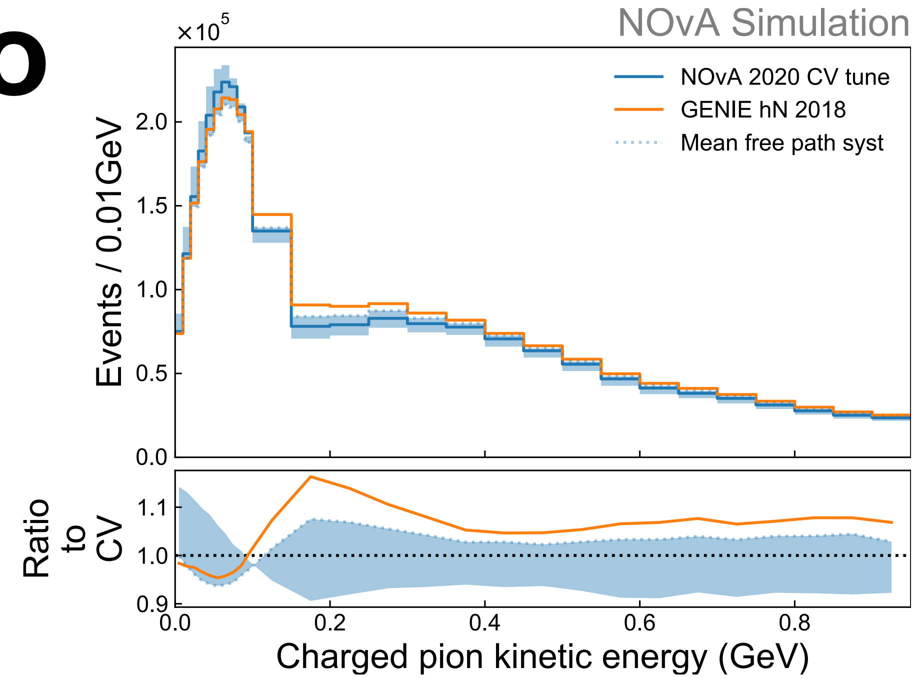
- To select an uncertainty for the MFP, we bracket the external data — in particular for the low KE region.
    - Our choice of values for MFP is 0.4 and 0.8.
- Note: We studied the correlations between the MFP and fABS, fCX, fQE.
    - Conclude the variations in the MFP are uncorrelated to the truth channel parameters.



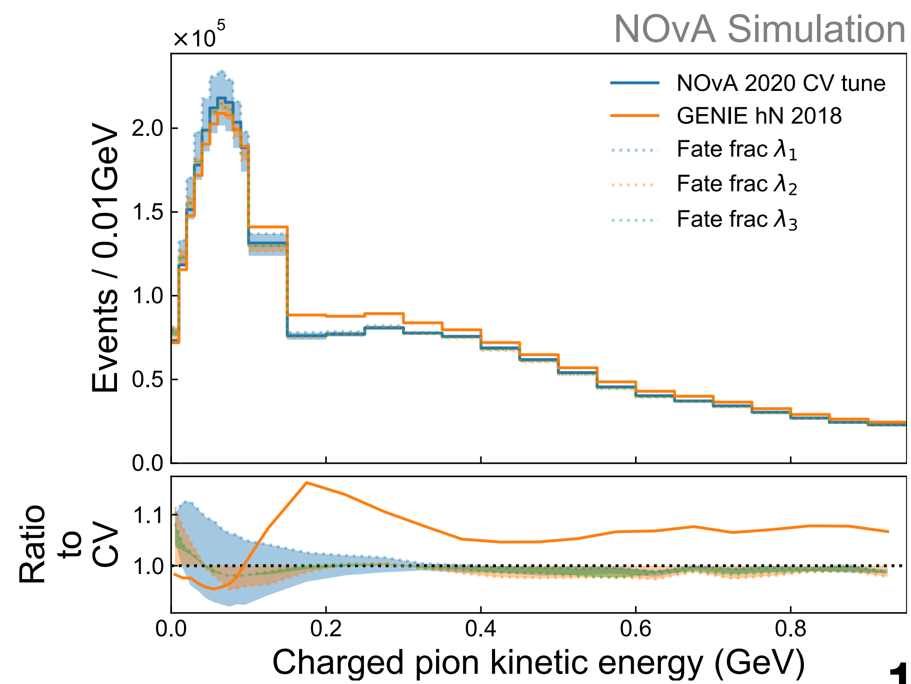
Impact on Neutrino Predictions

Impact on Neutrino Predictions

ν_μ CC RES & DIS in NOvA



- Here we show charged pion KE distributions and our uncertainties.
    - Uncertainties indicate a 5-10% variation on pion observables in our simulated neutrino samples.
- The blue error band (bottom) is the largest uncertainty.
    - Band is less than 0.1% uncertainty on NOvA oscillation measurements.



Summary

Quick review

1. Examine the hN model against pion scattering data, tuning the model to agree with the data.

2. Construct uncorrelated errors that can be treated independently, where none existed before.

3. These error variations create a 5-10% uncertainty on pion spectra, relevant for cross section analyses.

Thank You

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Back up

References

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1. C. Andreopoulos *et al*. *Nucl*. *Instrum*. *Meth*. A614: 87 (2010).
2. L. L. Salcedo *et al*. *Nucl*. *Phys*. A484: 557 (1988).
3. E.S. Pinzon Guerra et al. *Phys Rev*. D99: 052007 (2019).
4. A. Rogozhnikov. *J*. *Phys*. *Conf*. *Ser*. 762: 012036 (2016).

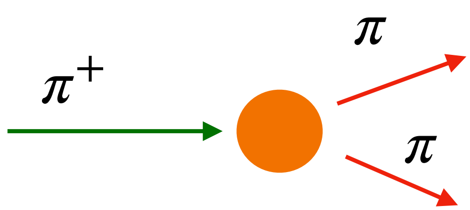
Pion Scattering Simulation & Data

Additional topological processes

- In addition to ABS, CX, & QE, there are two additional topological categories:

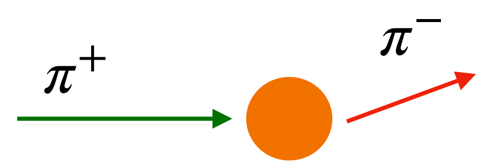
Hadron Production (HP)

At least two pions are observed in the final state.



Double Charge Exchange (DCX)

A single π^- is observed in the final state.

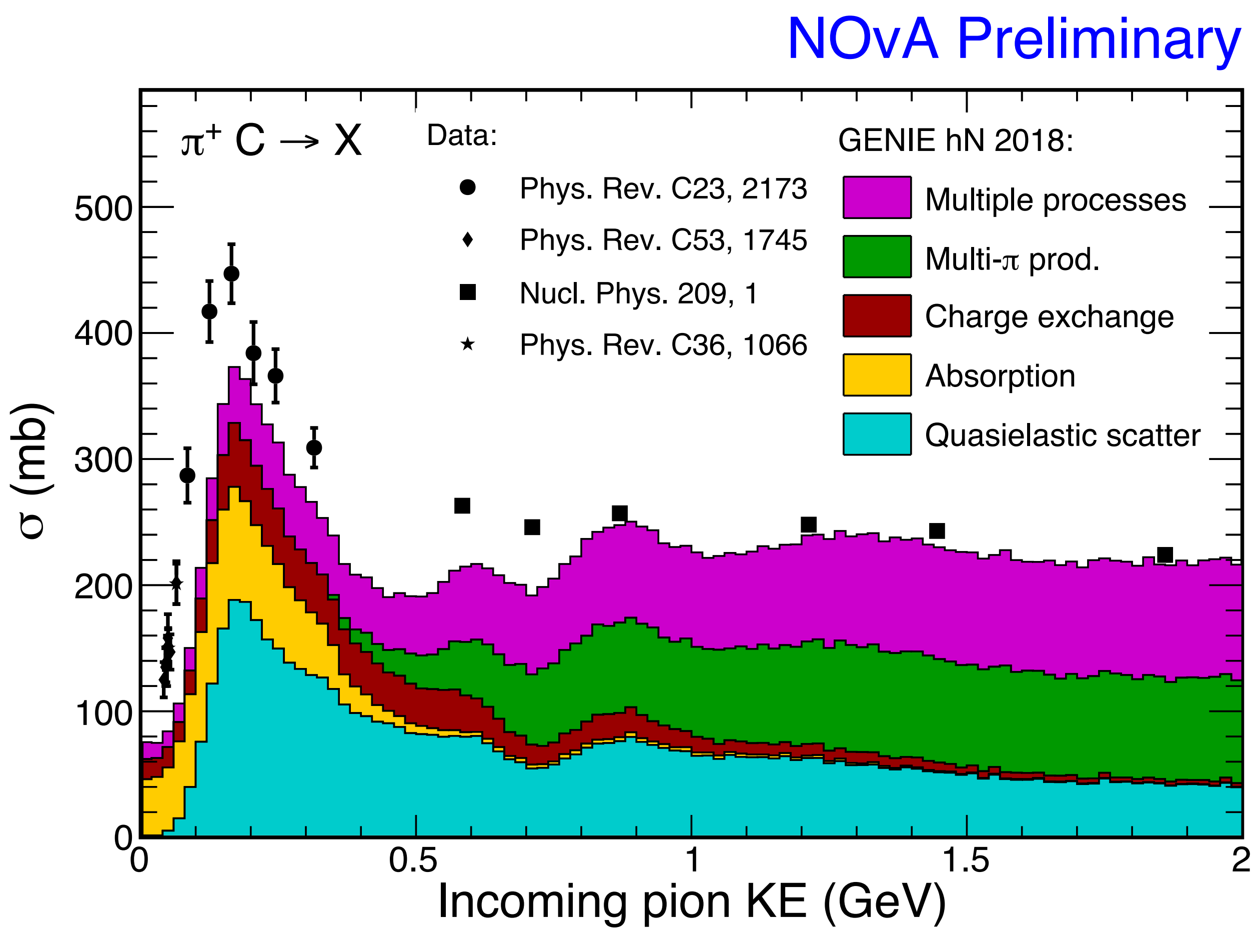


- These are not dominant processes and also occur at $KE_\pi > 500$ MeV/c, which is an unlikely kinematic region for FSI in NOvA.

Pion Scattering Simulation & Data

Additional topological processes

- HP and DCX are not dominant processes.
- They also occur at KE_{π} > 500 MeV, which is an unlikely kinematic region for FSI in NOvA.



Complete List of CV and Uncertainties

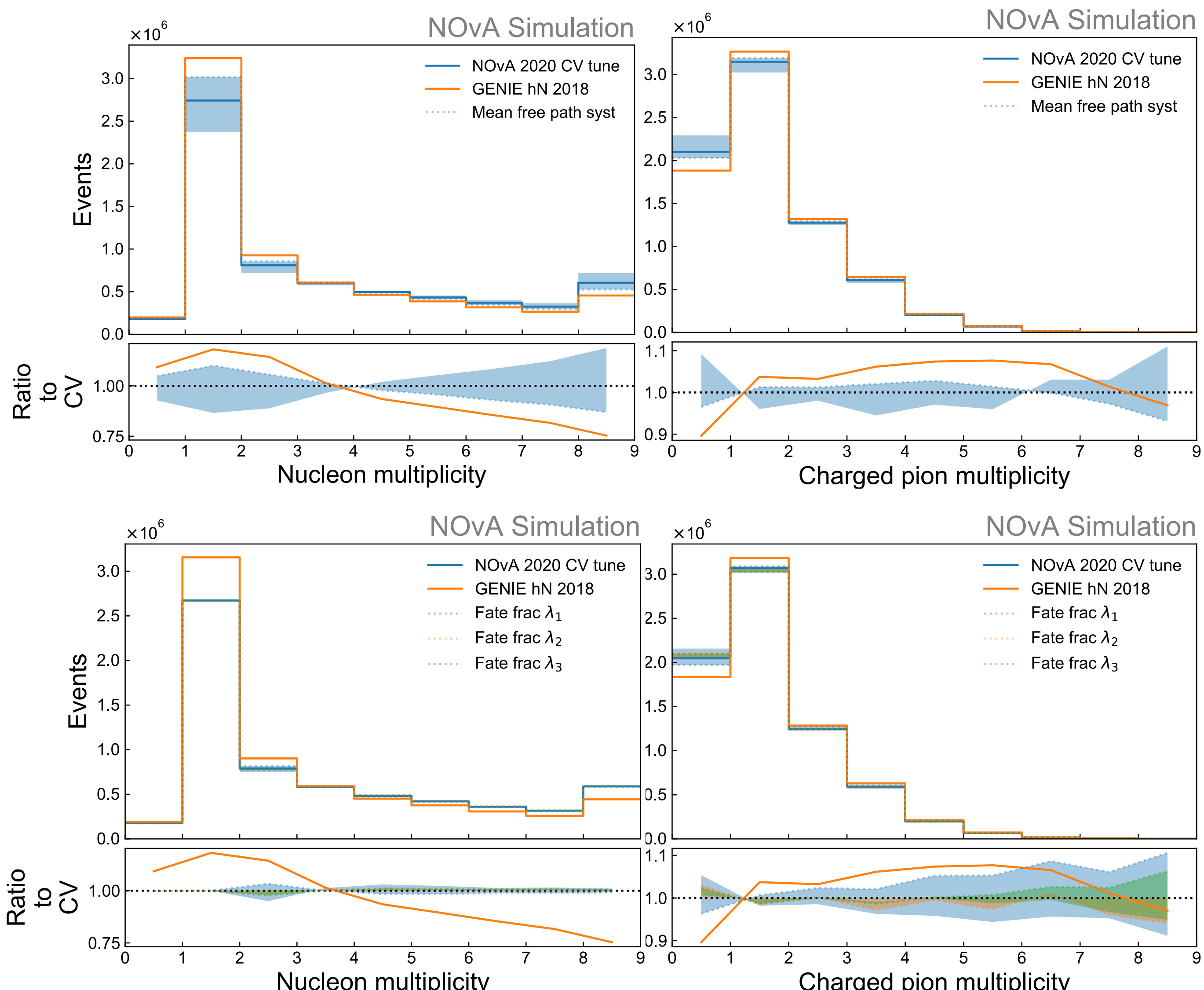
Process	Parameter	Value
Absorption	fABS	1.4
Charge Exchange	fCX	0.7
Quasi-Elastic	fQE	0.9
REAC	MFP	0.6

Knob	Shift (1σ)	fMFP	fABS	fCX	fQE
# 1	plus	0.6	0.9	0.8	1.0
	minus	0.6	1.8	0.6	0.8
# 2	plus	0.6	1.4	0.9	0.7
	minus	0.6	1.4	0.5	1.2
# 3	plus	0.6	1.3	0.5	0.8
	minus	0.6	1.4	0.8	1.0
MFP	plus	0.4	1.4	0.7	0.9
	minus	0.8	1.4	0.7	0.9

Impact on Neutrino Predictions

ν_μ CC RES & DIS in NOvA

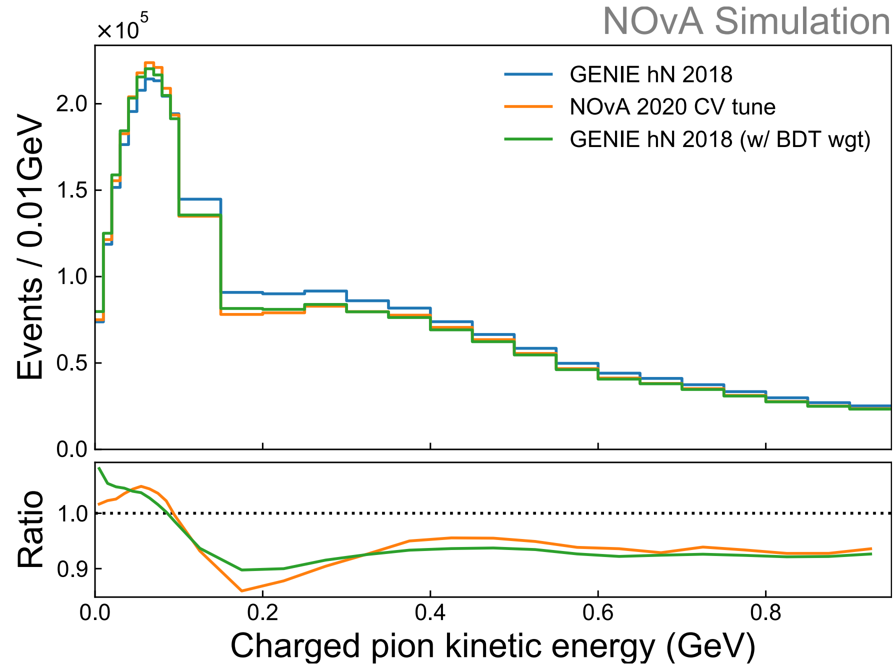
- Additional plots of our generated neutrino sample.
    - Plotted with our uncorrelated error bands are multiplicities of:
        - nucleons.
        - charged pions.

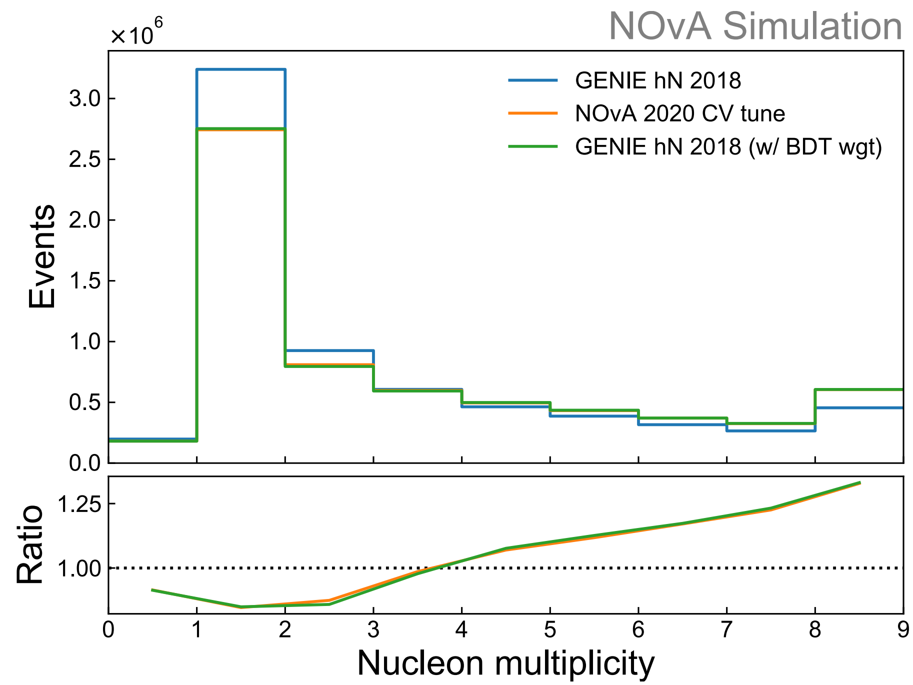


Boosted Decision Trees

How can we reweight simulation that's already made?

- Our nominal 2020 simulation has already been produced.
- Our solution is to utilize Boost Decision Trees (BDT) to reweight our existing simulation, with nominal hN, to our hN CV-tuned values [4].
- We can see the nominal production reweighted by the BDT in green are well replicated to our CV tune in orange.





Boosted Decision Trees

Closure test for our BDT

- Additionally, we want to ensure we do not reweight other, non-FSI useful truth variables.

    - We show the Q^2 distribution demonstrating our BDT only reweights the variables we desire.