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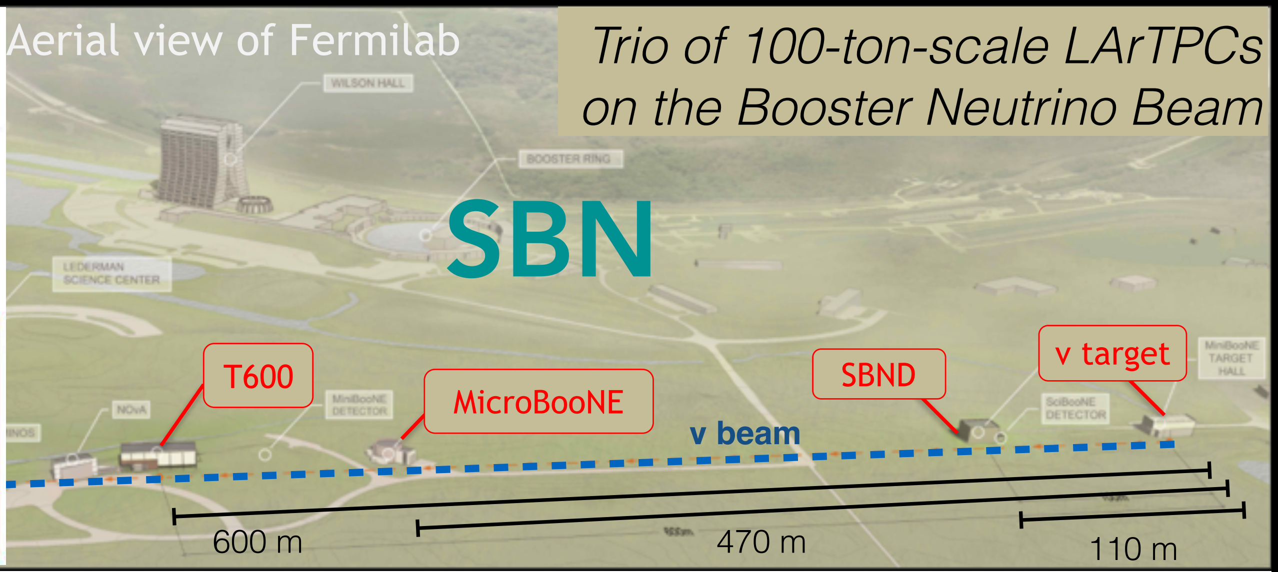
NUCLEAR EFFECTS IN NEUTRINO OSCILLATION EXPERIMENTS

QNP2022
THE 9TH INTERNATIONAL CONFERENCE ON QUARKS AND NUCLEAR PHYSICS

NEUTRINO OSCILLATION EXPERIMENTS

- Many neutrino oscillation experiments have been built using neutrino beams produced by accelerators around the World: US (NuMI and Booster), Europe (CNGS) and Japan (JPARC).

- The baseline of these experiments go from few hundreds of meters (short-baseline) to hundreds (300-1300) of km (long-baseline).



NEUTRINO OSCILLATION EXPERIMENTS

- Precision is achieved by placing a detector close to the source (Near Detector) and one at or close to the oscillation maximum (Far Detector).

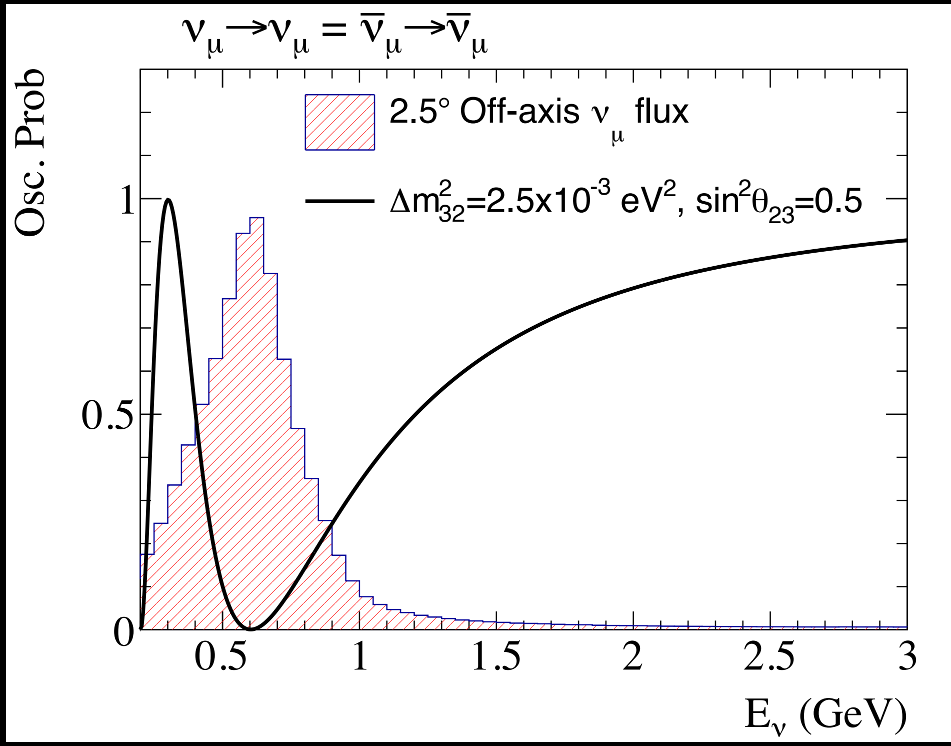
$$R_{ND}(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND}$$
$$R_{FD}(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P_{osc}$$

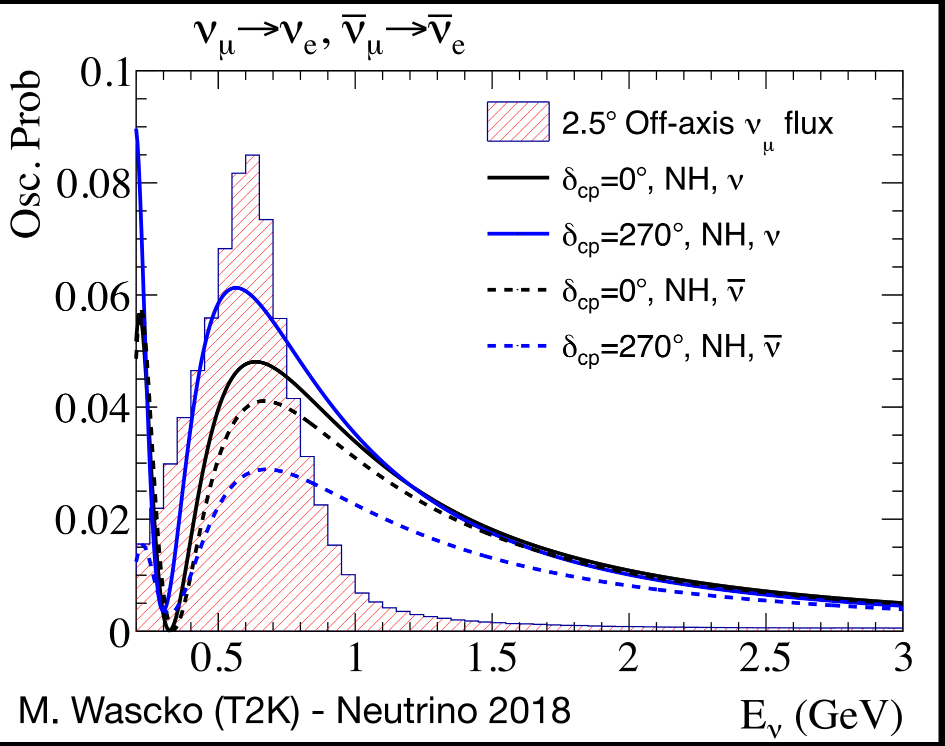
- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
- The measured spectrum is used to make a prediction of the expectation at the FD before considering oscillations.

UNDERSTANDING THE FLUX, **NEUTRINO INTERACTIONS** AND DETECTOR EFFICIENCIES IS ESSENTIAL FOR HIGH PRECISION

NEUTRINO OSCILLATION EXPERIMENTS

MEASURING OSCILLATION PARAMETERS REQUIRES PRECISION IN ENERGY RECONSTRUCTION





- In order to measure oscillation parameters we measure two channels: muon neutrinos disappearance and electron neutrino appearance.
- These measurements allow us to probe CP violation, the mass ordering as well as the mass difference and mixing angles.

OBTAINING NEUTRINO ENERGY IN NEUTRINO OSCILLATION EXPERIMENTS

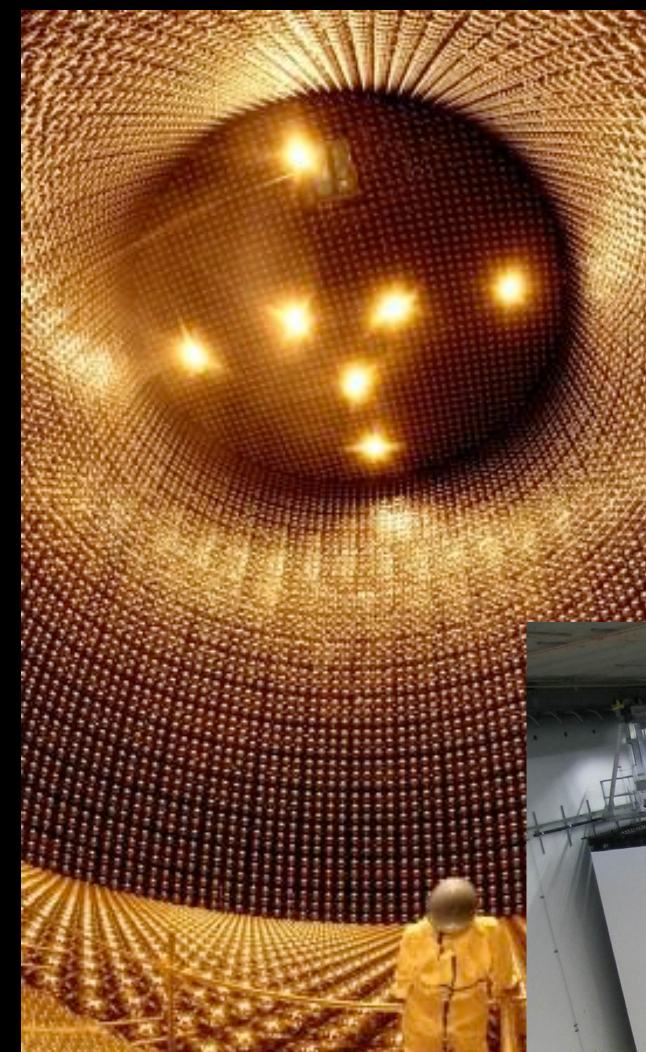
- Since the oscillation probability depends on neutrino energy, we must reconstruct energy precisely.

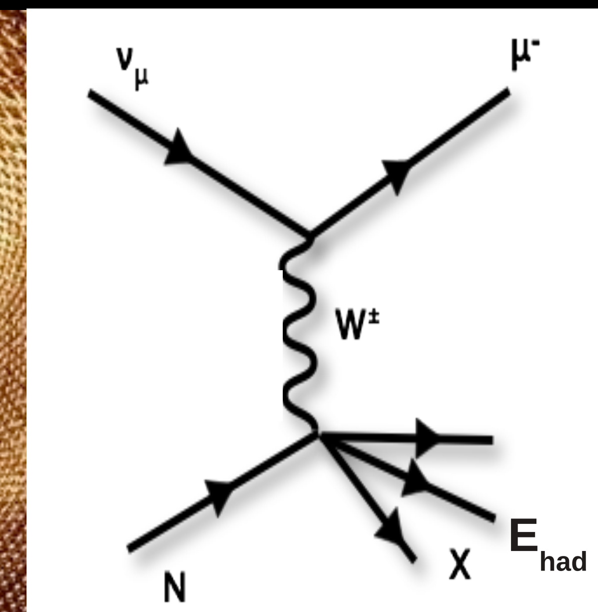
- Neutrino energy reconstruction is obtained using the final state particles of neutrino-nucleus interactions.

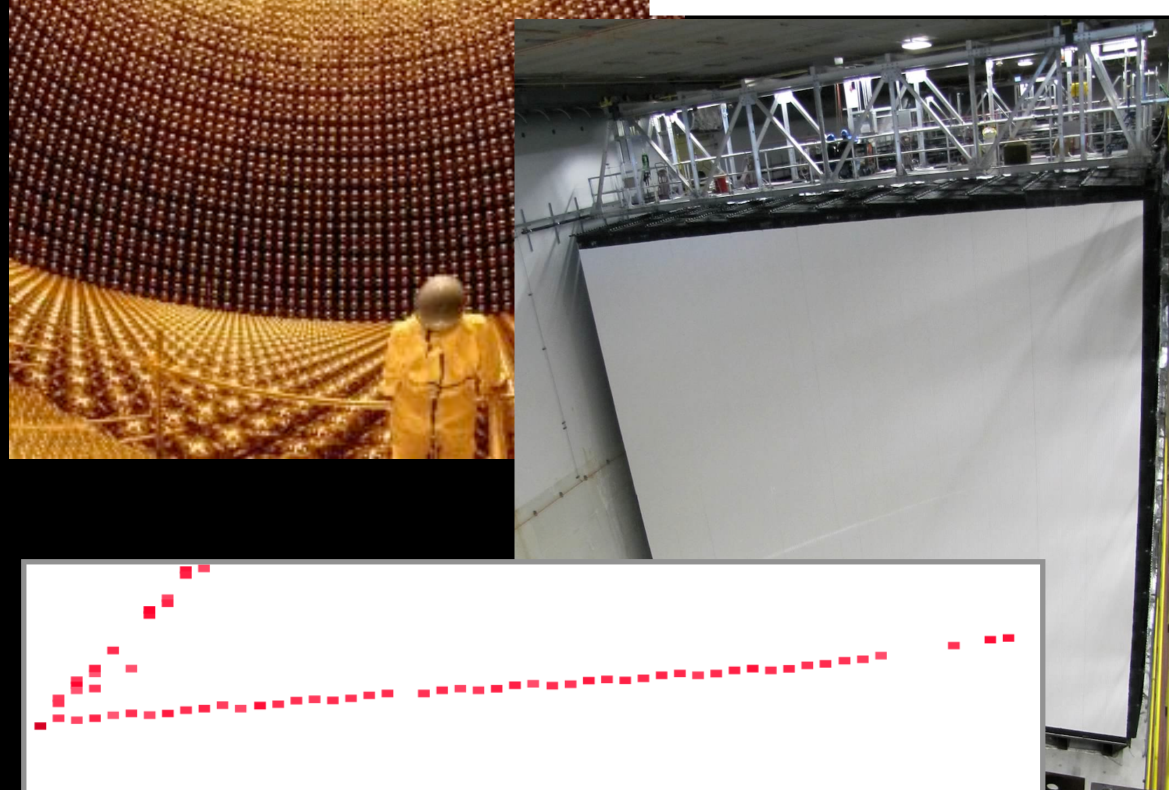
    - Non fully active experiments, rely on the kinematics of the outgoing lepton to determine the energy.

    - Fully active experiments reconstruct the energy using the sum of the lepton and hadronic energies.

- Nuclear effects modify the kinematics of the particles and therefore the reconstruction of the neutrino energy.

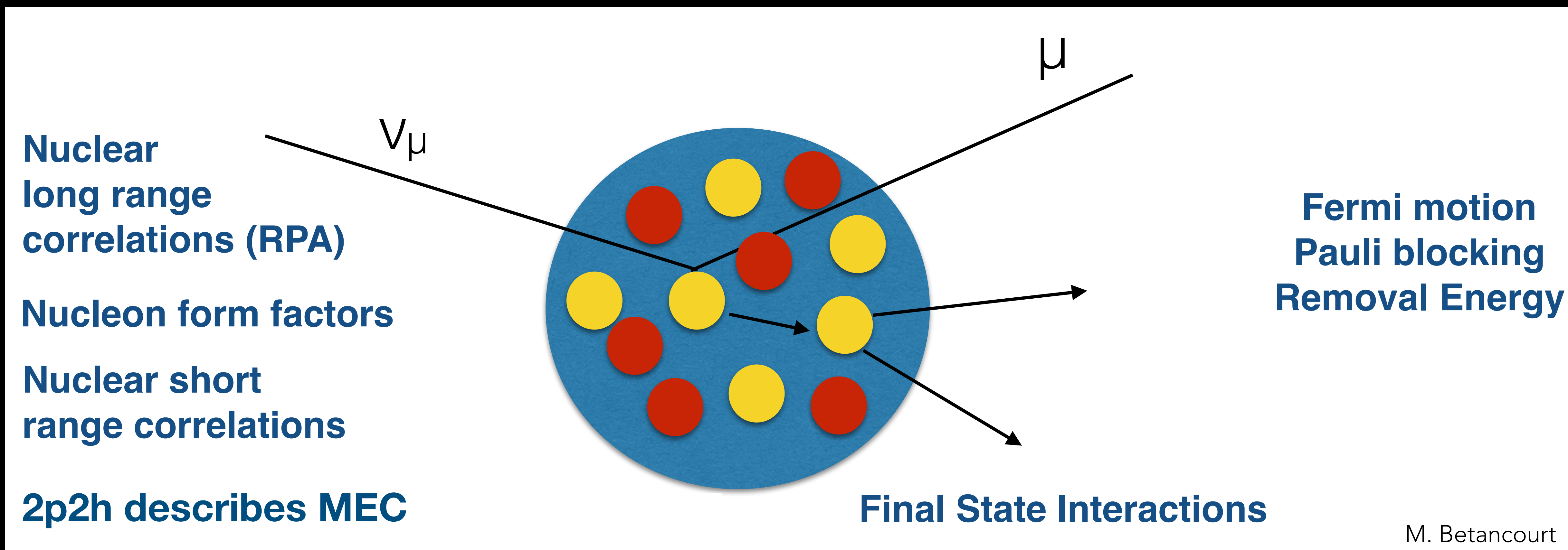




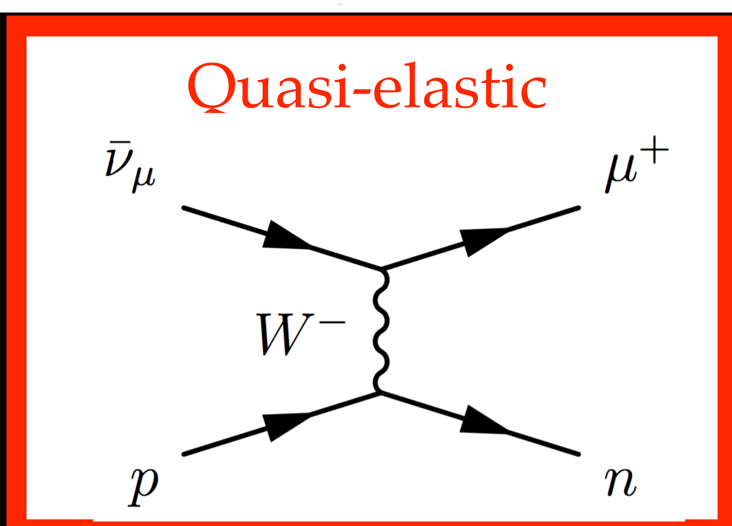


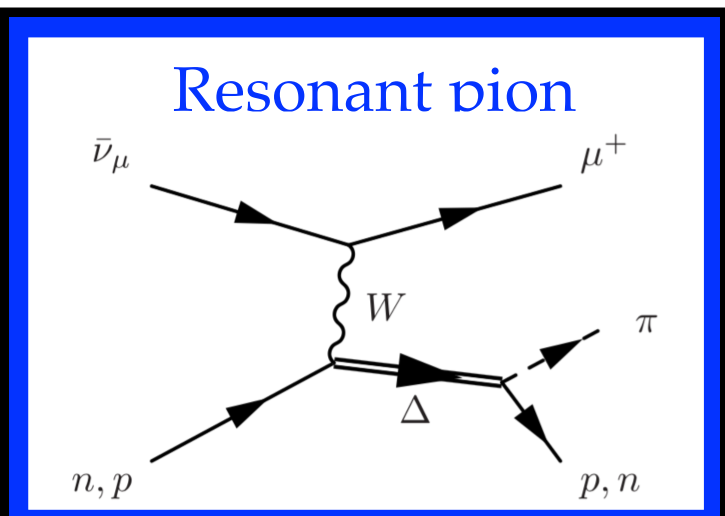
NEUTRINO NUCLEUS SCATTERING

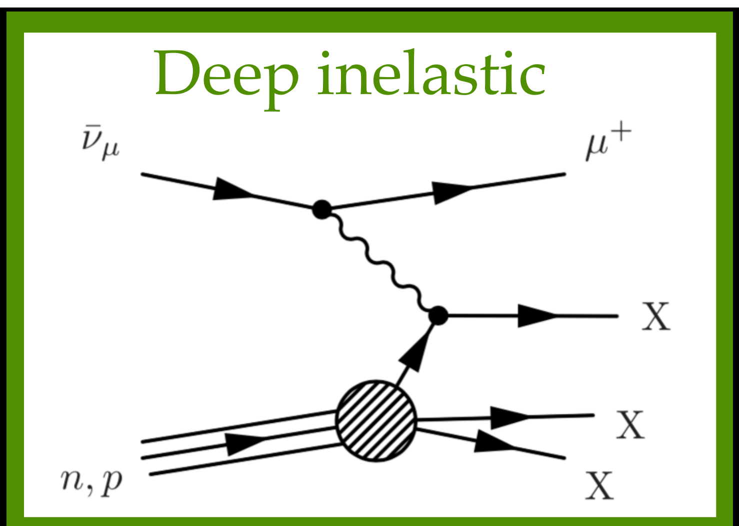
- Understanding neutrino nucleus interactions is challenging; interplay of many different effects.



Free nucleon interactions







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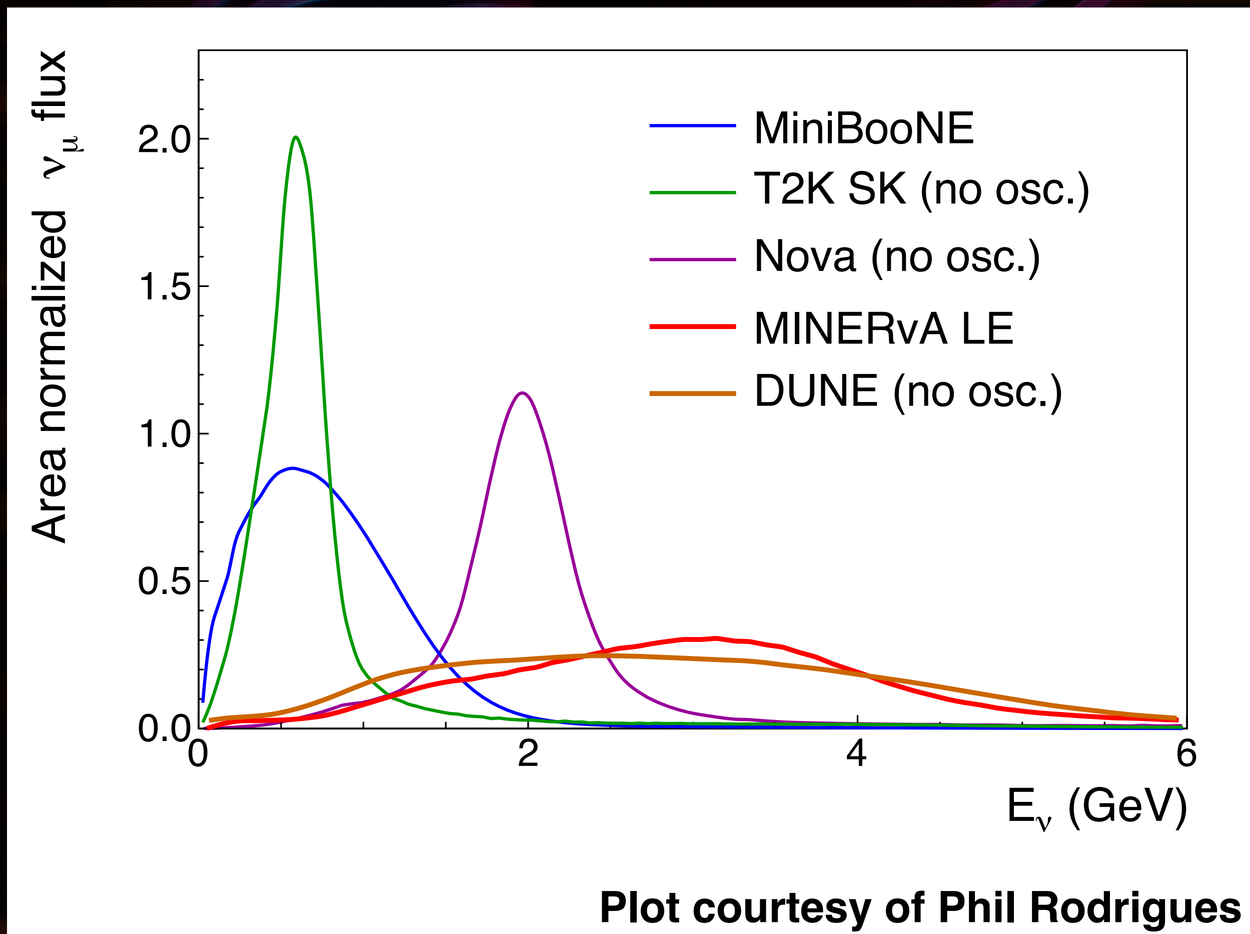
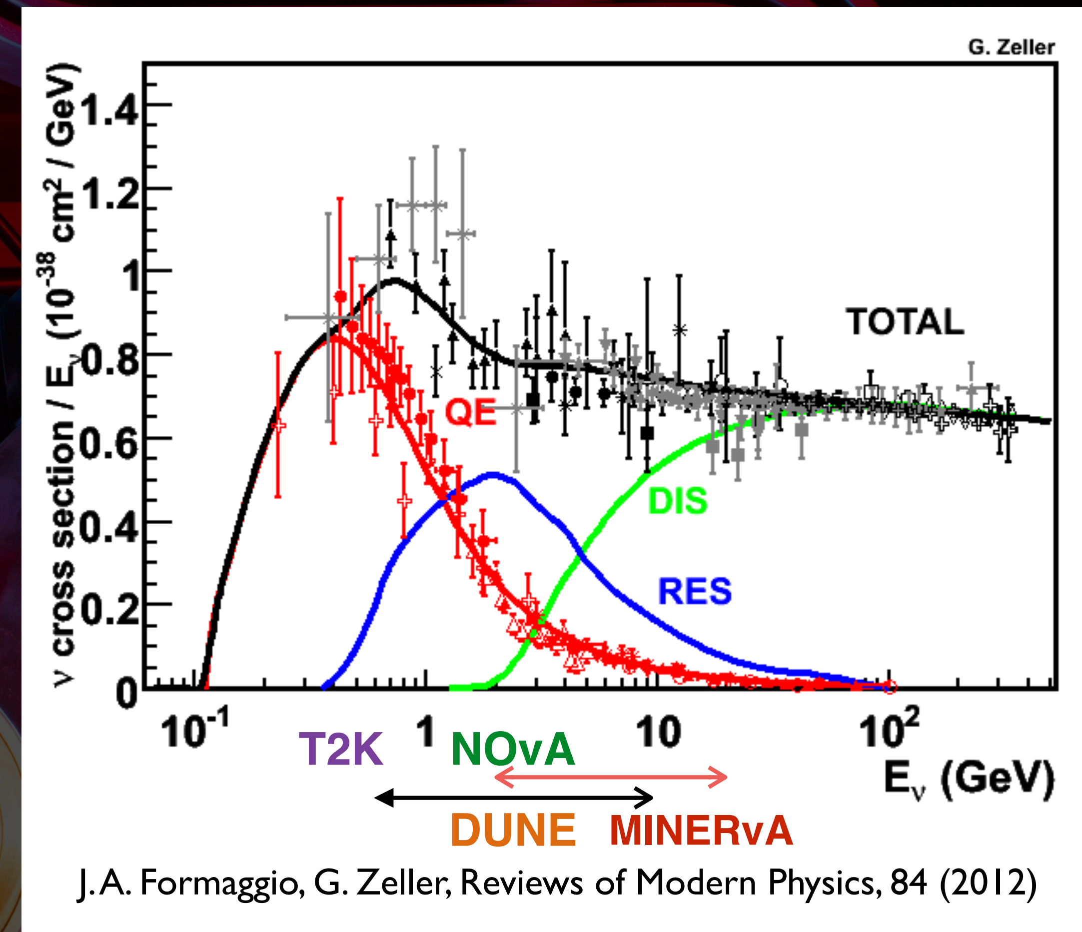
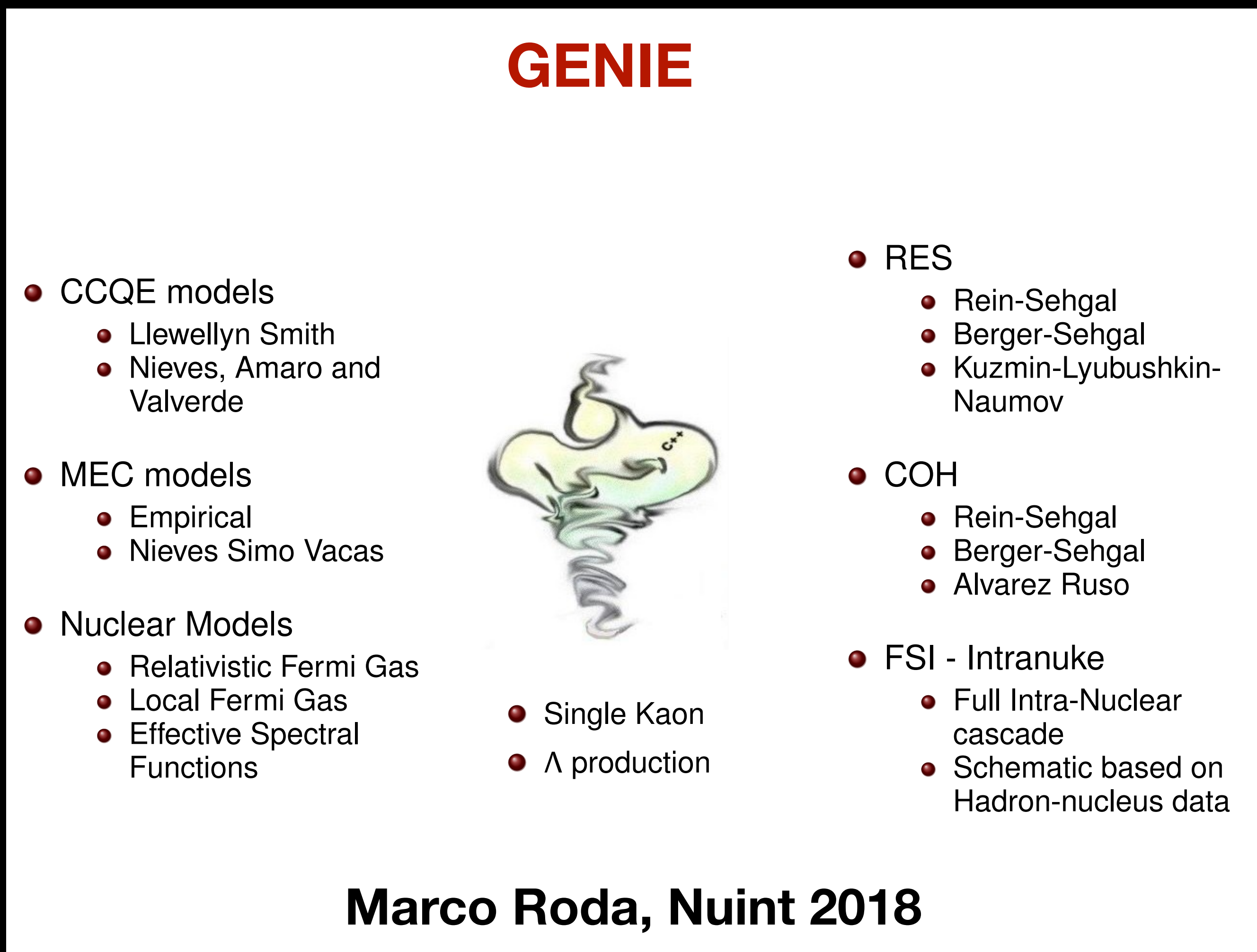
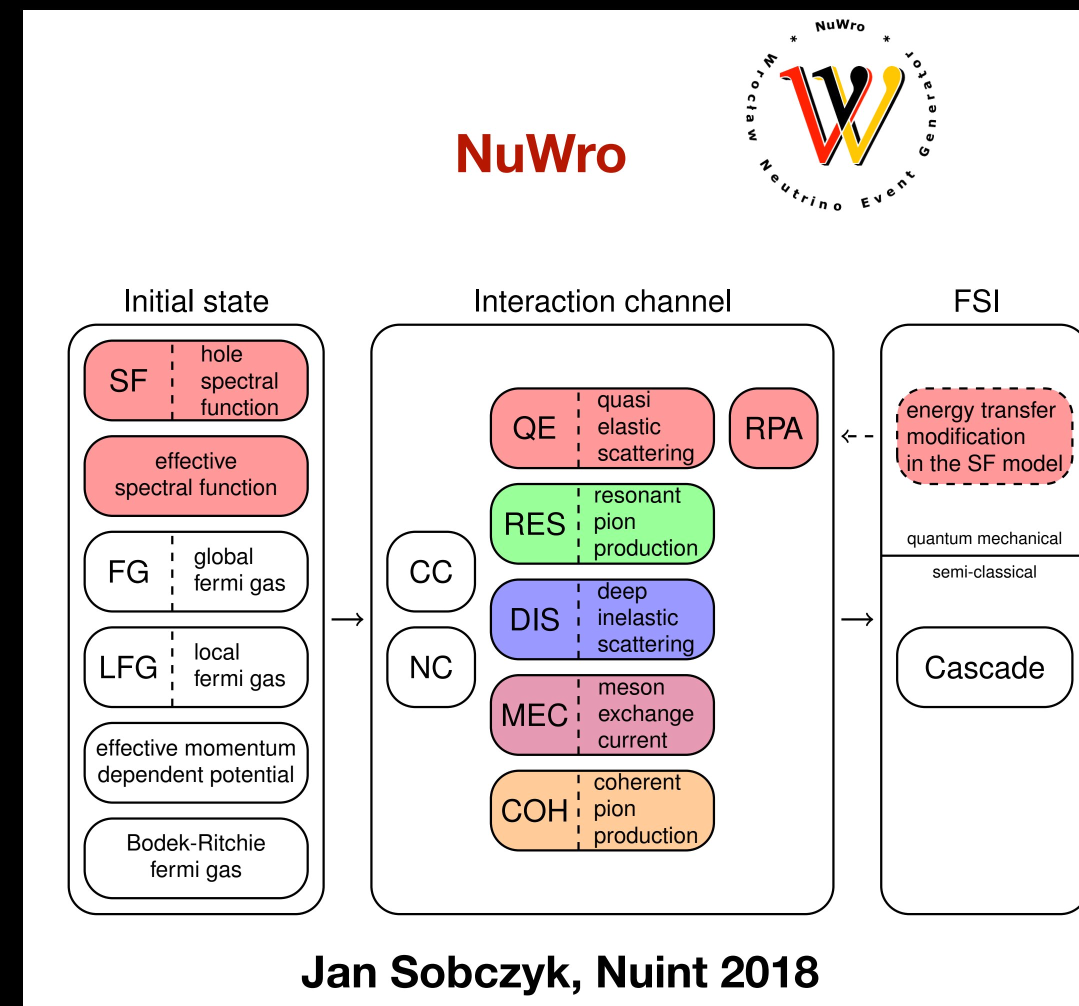




- Current neutrino experiments explore different energy regimes and are dominated by different cross sections channels.
- Significant progress on the simplest of interactions CCQE (0π). Recent interest on the pion production channels both for NOvA and T2K. Next challenge is DIS which will be important for DUNE.

NEUTRINO INTERACTION GENERATORS





- Several neutrino interaction simulations are used in the field: GENIE, NEUT, NuWro and GiBUU. Experiment choose their own, potentially choose a configuration and further adjust to match their data.

SIGNIFICANT SYSTEMATIC UNCERTAINTIES FOR OSCILLATION EXPERIMENTS

Source of uncertainty	ν_e signal (%)	Total beam background (%)
Cross sections and FSI	7.7	8.6
Normalization	3.5	3.4
Calibration	3.2	4.3
Detector response	0.67	2.8
Neutrino flux	0.63	0.43
ν_e extrapolation	0.36	1.2
Total systematic uncertainty	9.2	11
Statistical uncertainty	15	22
Total uncertainty	18	25

Phys. Rev. D 91.072010

NOvA

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

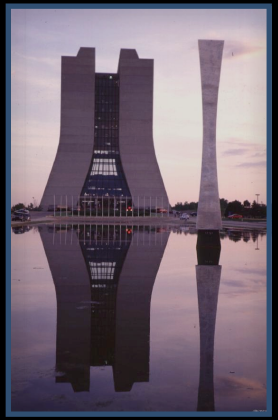
T2K

Phys. Rev. D 98.032012

- The uncertainties arising from cross sections and final state interactions represent a significant source of uncertainty for oscillation experiments.

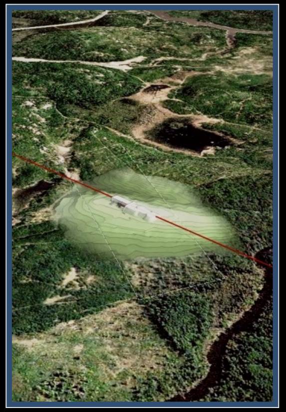
THE NOVA EXPERIMENT IN A NUTSHELL

- High intensity NuMI **beam of muon neutrinos** at Fermilab with 700kW.
- Highly active liquid scintillator (carbon target nucleus) **14-kton detector** off the main axis of the beam.
- Study the millions of neutrino interactions at a Near Detector location.
- If neutrinos oscillate, **muon neutrinos disappear** as they travel and **electron neutrinos appear** at the Far Detector in Ash River,
  810 km away.



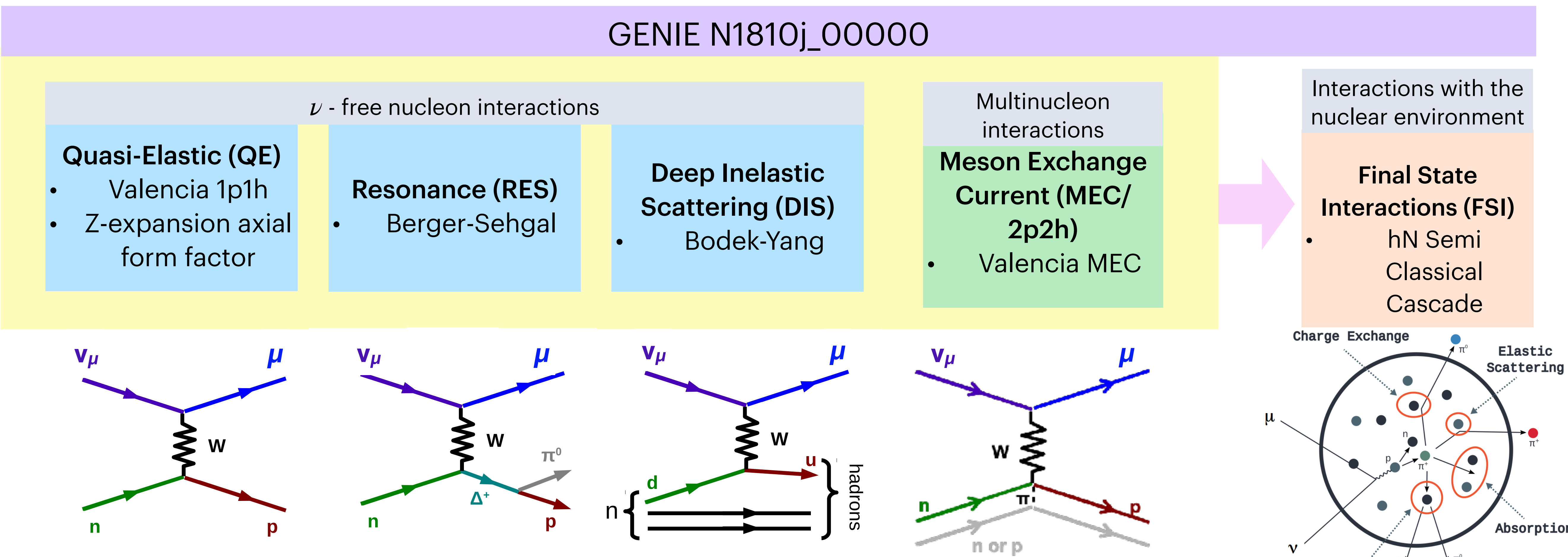
2nd generation
← long baseline →

L/E ~ 500 km



NEUTRINO INTERACTIONS SIMULATION IN NOVA

- Neutrino interactions are simulated using GENIE v3.0.6

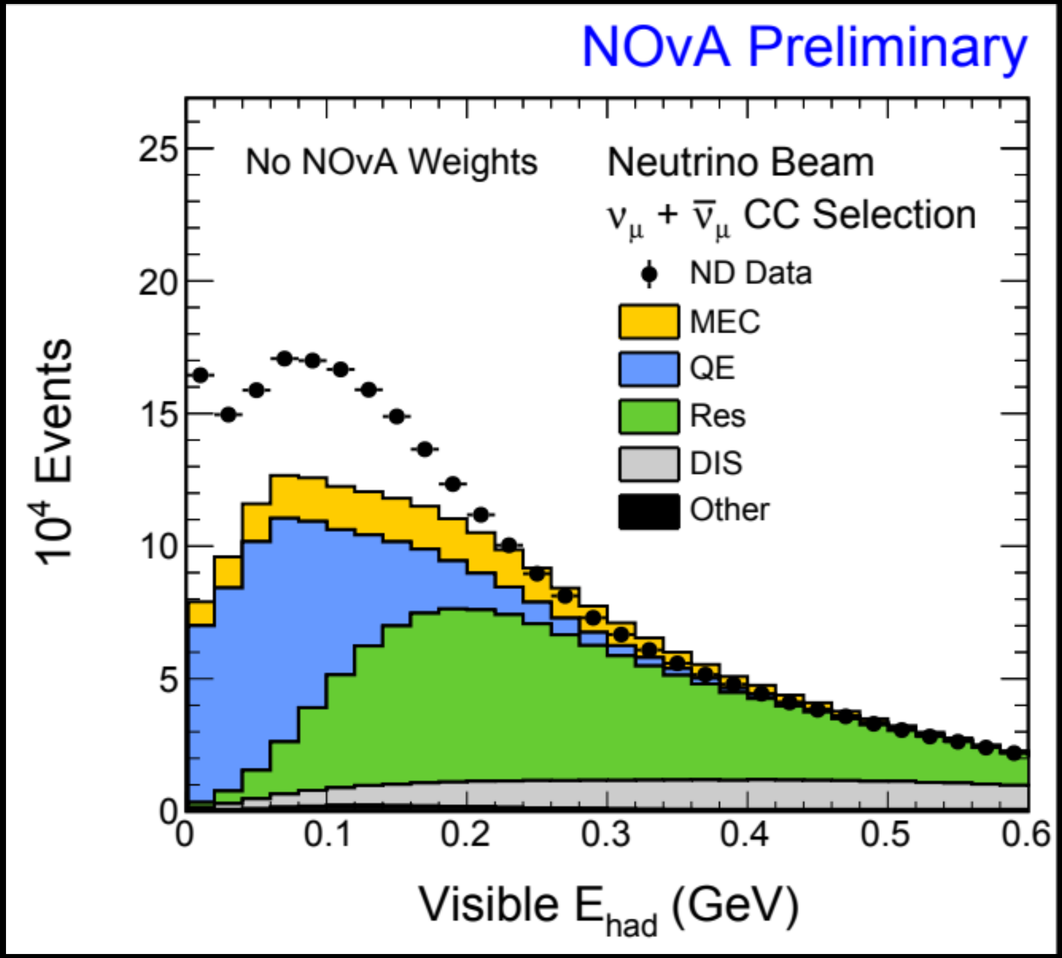


M. Martinez-Casales (NOvA)

- In addition to free nucleon interactions; multinuclear interactions and nuclear effects complete the picture of neutrino interactions.

NEUTRINO INTERACTIONS IN NOVA

- The Default GENIE prediction is insufficient to describe the muon neutrino selection of NOvA ND data, e.g. the hadronic energy in **ν_μ** CC interactions show disagreement with the default simulation.
- This is a rich data set with extremely high statistics.
- Discrepancies thought to be due largely to complications of interactions in complex nuclear environment.
- Adjustments of final state interactions and 2p2h are required to obtain better agreement.

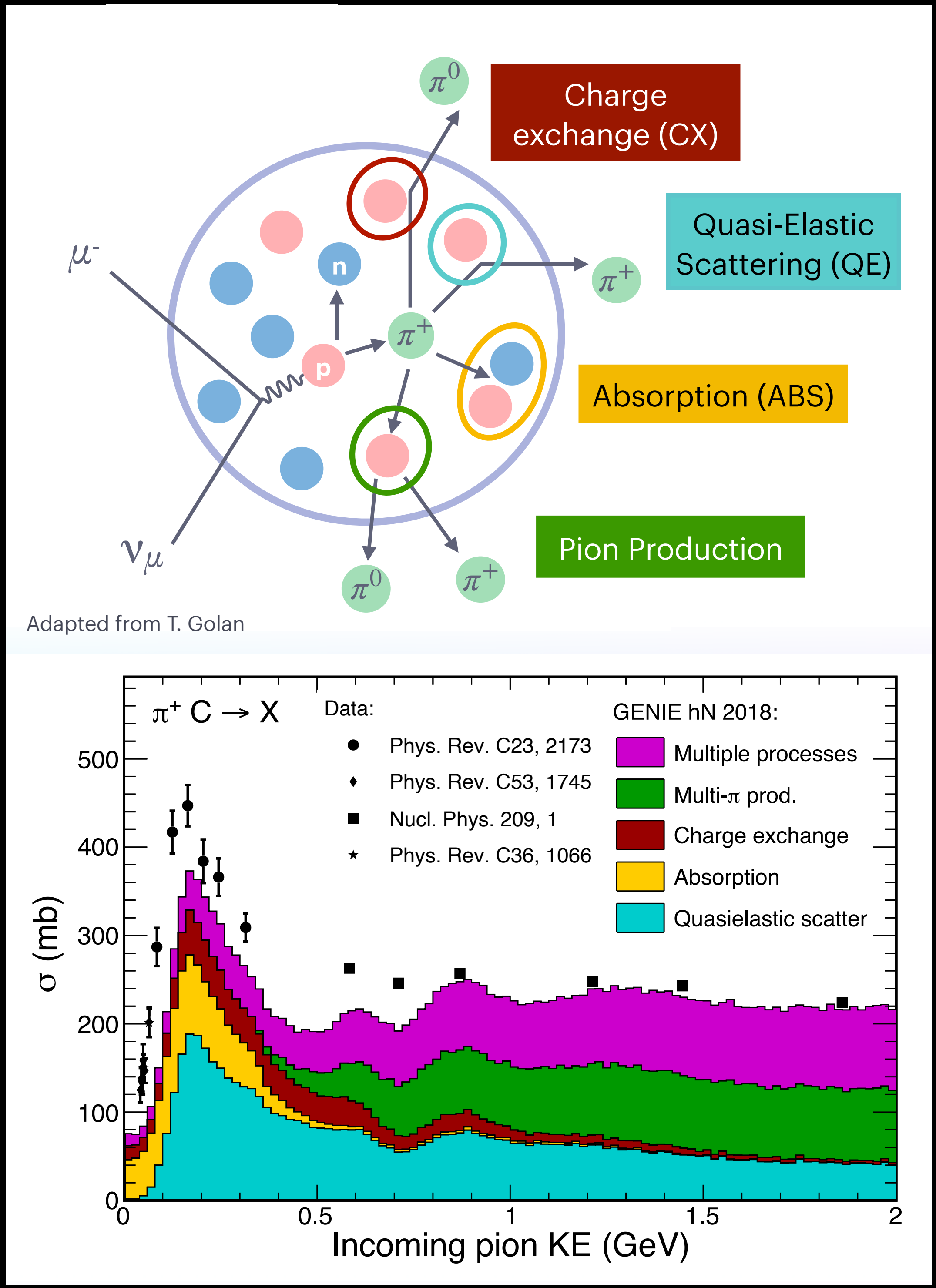


WE USE **NOVA AND EXTERNAL INFORMATION** TO TUNE THE MODEL TO OBTAIN BETTER CENTRAL VALUES AND APPROPRIATE UNCERTAINTIES

FINAL STATE INTERACTIONS

- Due to final state interactions, nucleons and pions re-interact when propagated through the nuclear medium before are observed: charge exchange, pion absorption, pion production, etc.

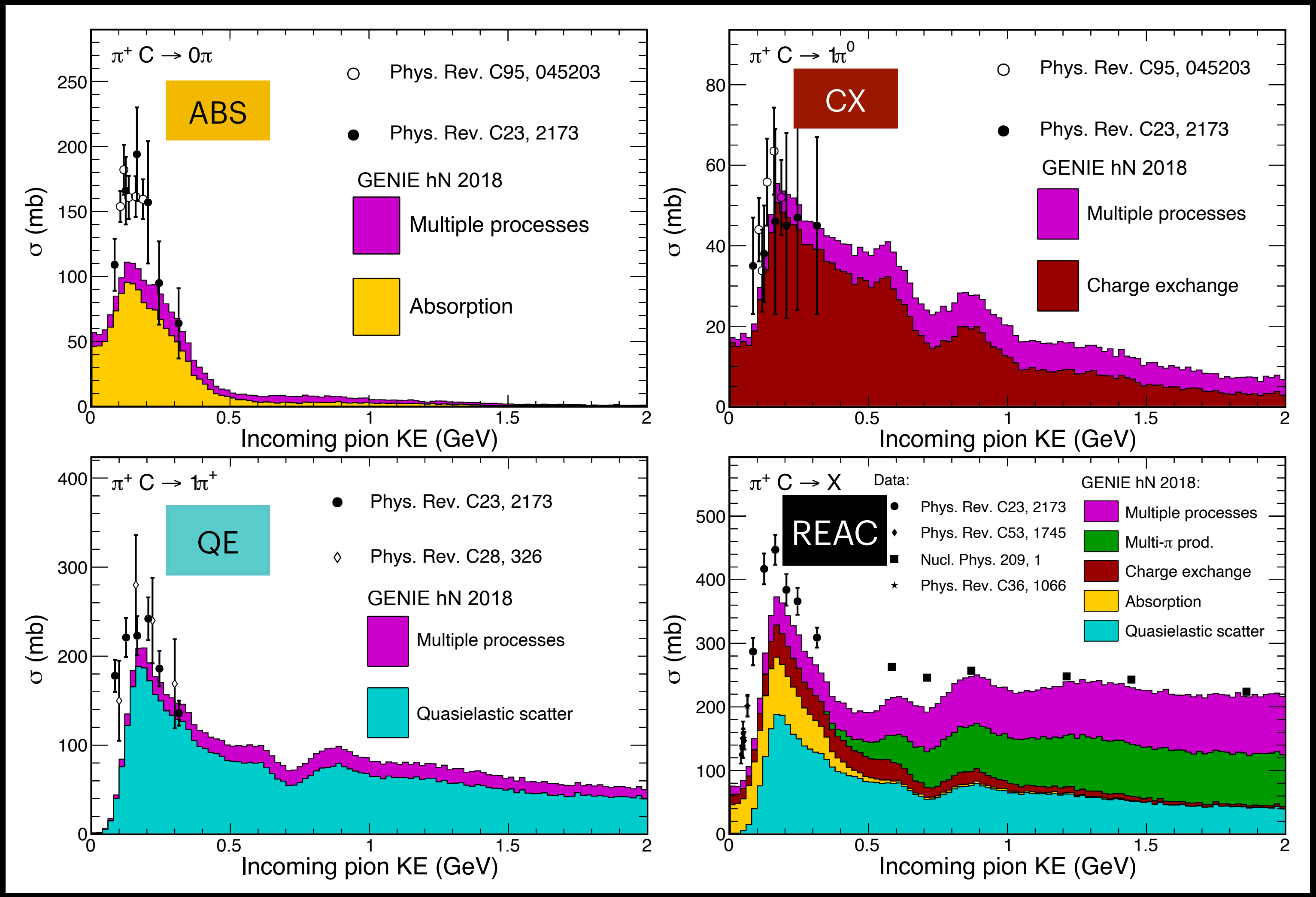
- Genie hN model agreement with π^+ ^{12}C scattering data is poor.



FINAL STATE INTERACTIONS

- Total "reactive" cross section is the sum of these processes.
- NOvA adjusts:
  - The "fate fractions" for these 3 channels.
  - Mean Free Path (MFP) which scales inversely with cross section.
- The MFP is tuned with a 40% reduction and the "absorption" prediction is increased by 40%.

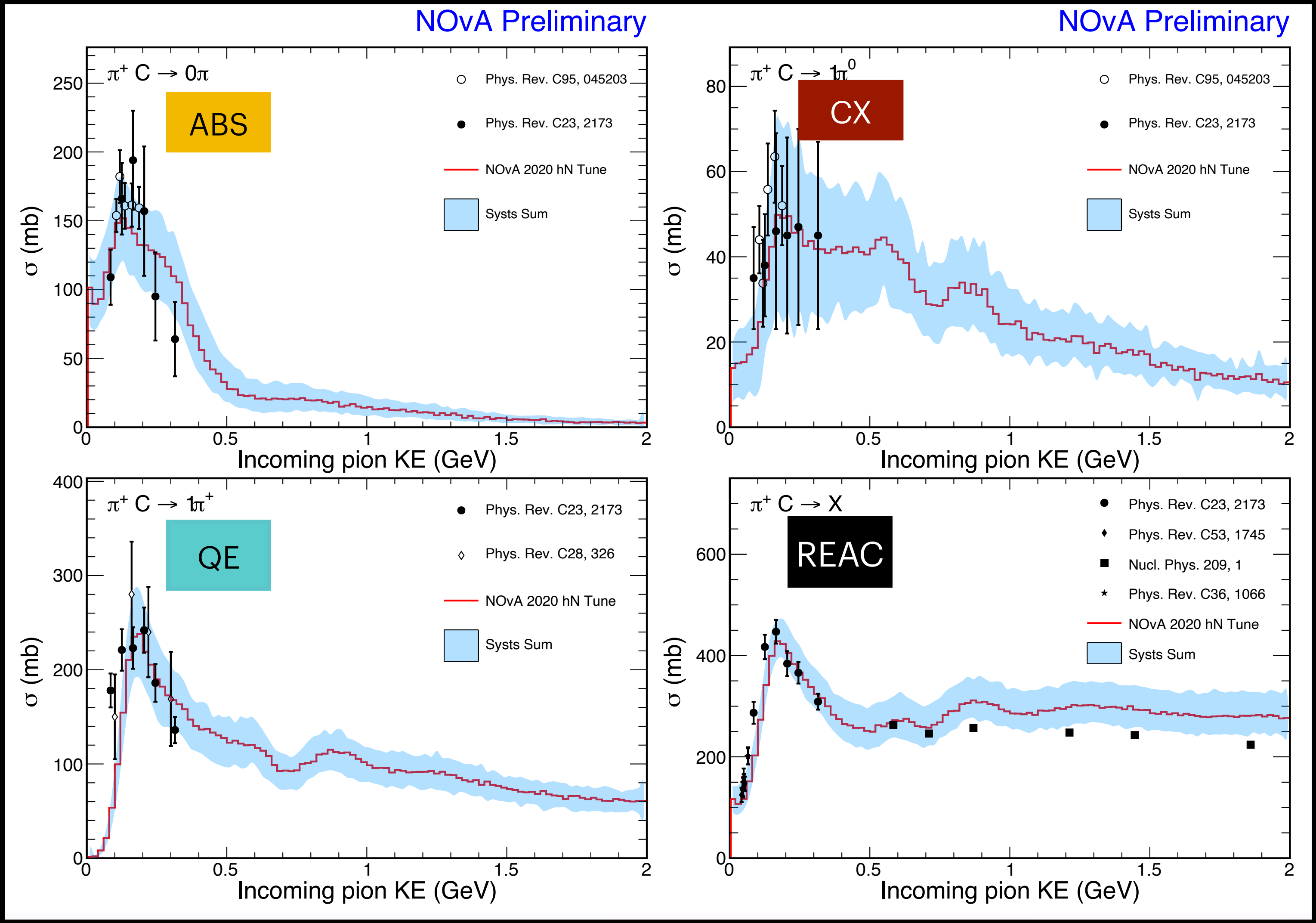
- Pion scattering data can be categorized into the topological channels based on the outgoing particles.



FINAL STATE INTERACTIONS

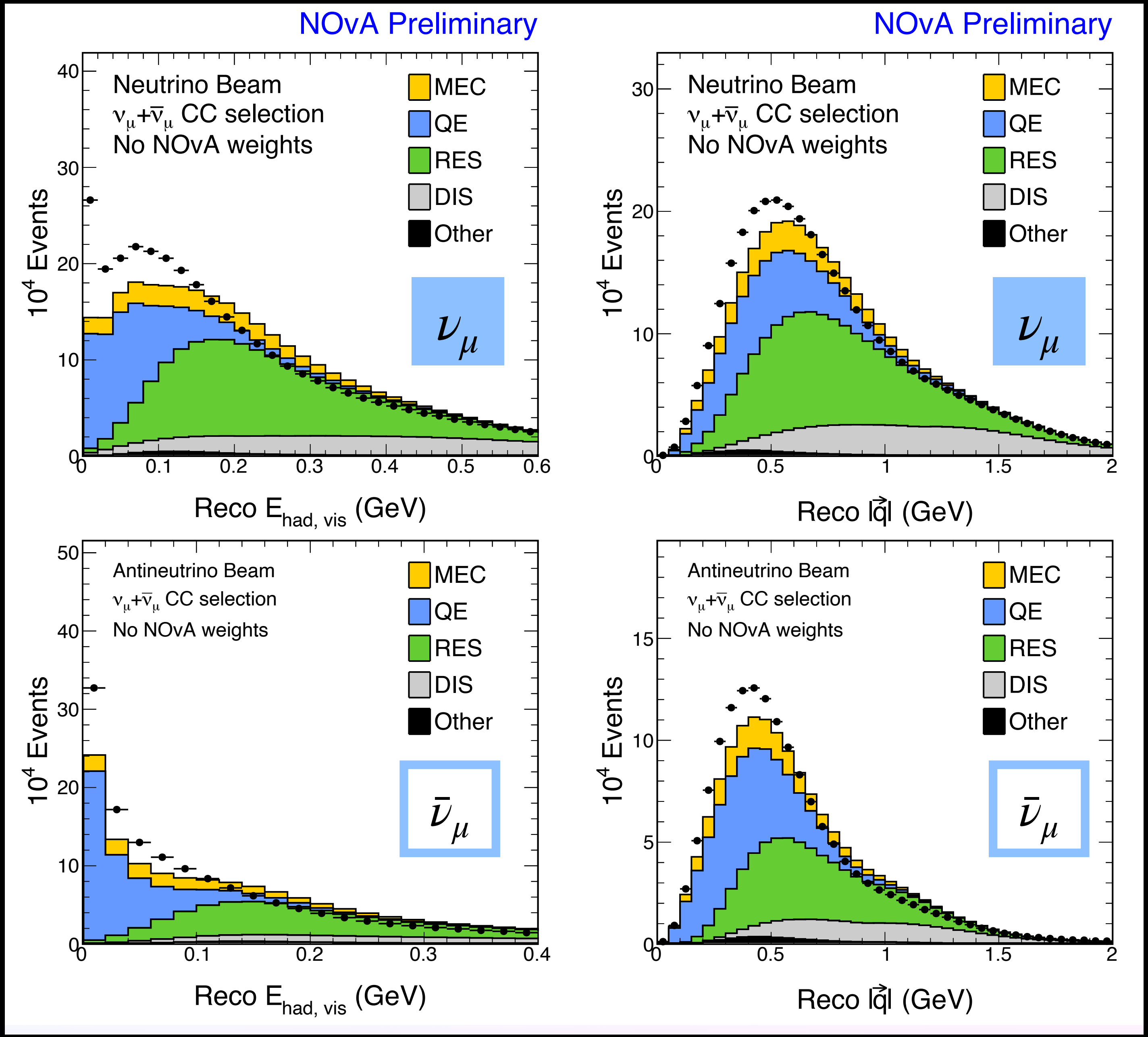
- After tuning, four uncorrelated uncertainties are constructed:
  - 3 uncorrelated uncertainties of the "fate fractions".
  - MFP uncertainty is constructed with the values of this parameter that bracket the external data.

- The pion observables compared to the neutrino prediction, with a single error band, from the 4 uncorrelated error variations added in quadrature.



MULTI-NUCLEON INTERACTIONS (2P2H)

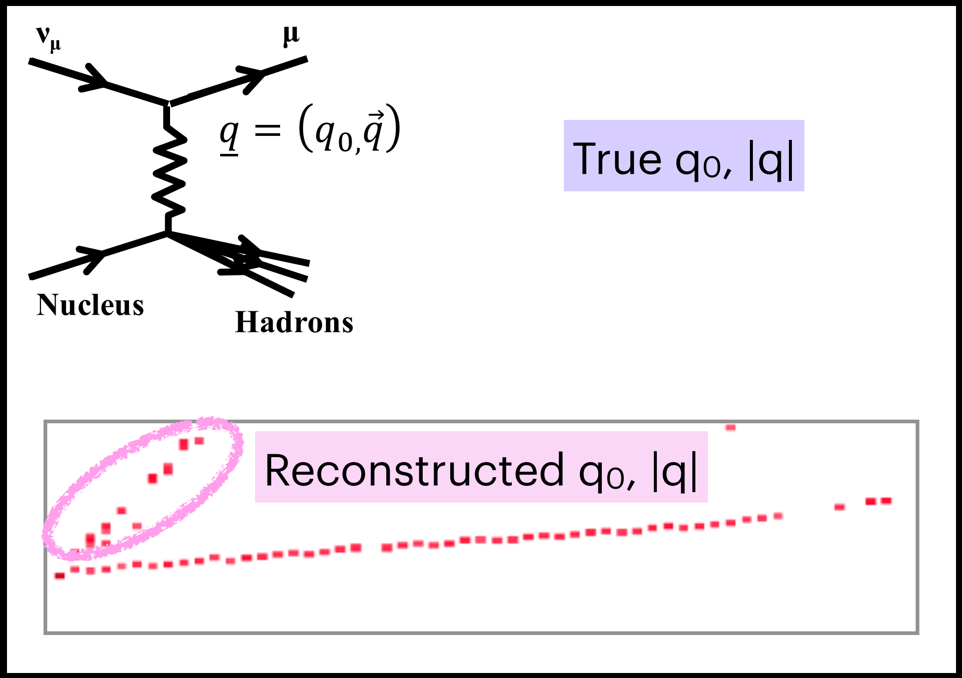
- Introduce custom tuning of GENIE "Valencia MEC" **based on NOvA ND data.**
- Adjustment reshapes MEC kinematics to match data, effectively adding missing processes (like short range correlations between nucleons)
- This tuning procedure matches the 2p2h component to the NOvA data excess in two-dimensional four-momentum transfer (q0,|**q**|) space using closely-related related observables.

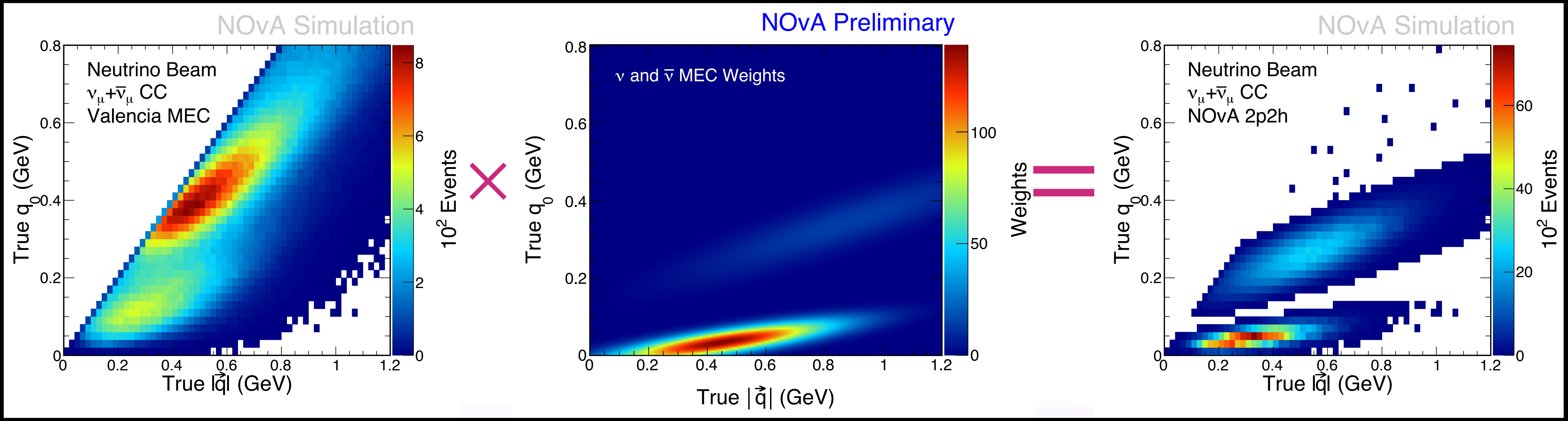


before the tune

MULTI-NUCLEON INTERACTIONS (2P2H)

- Model is parameterized as two 2d gaussians and normalization resulting in 13 parameters.
- Same weights are used for neutrino and anti-neutrino resulting in good agreement for both data sets.





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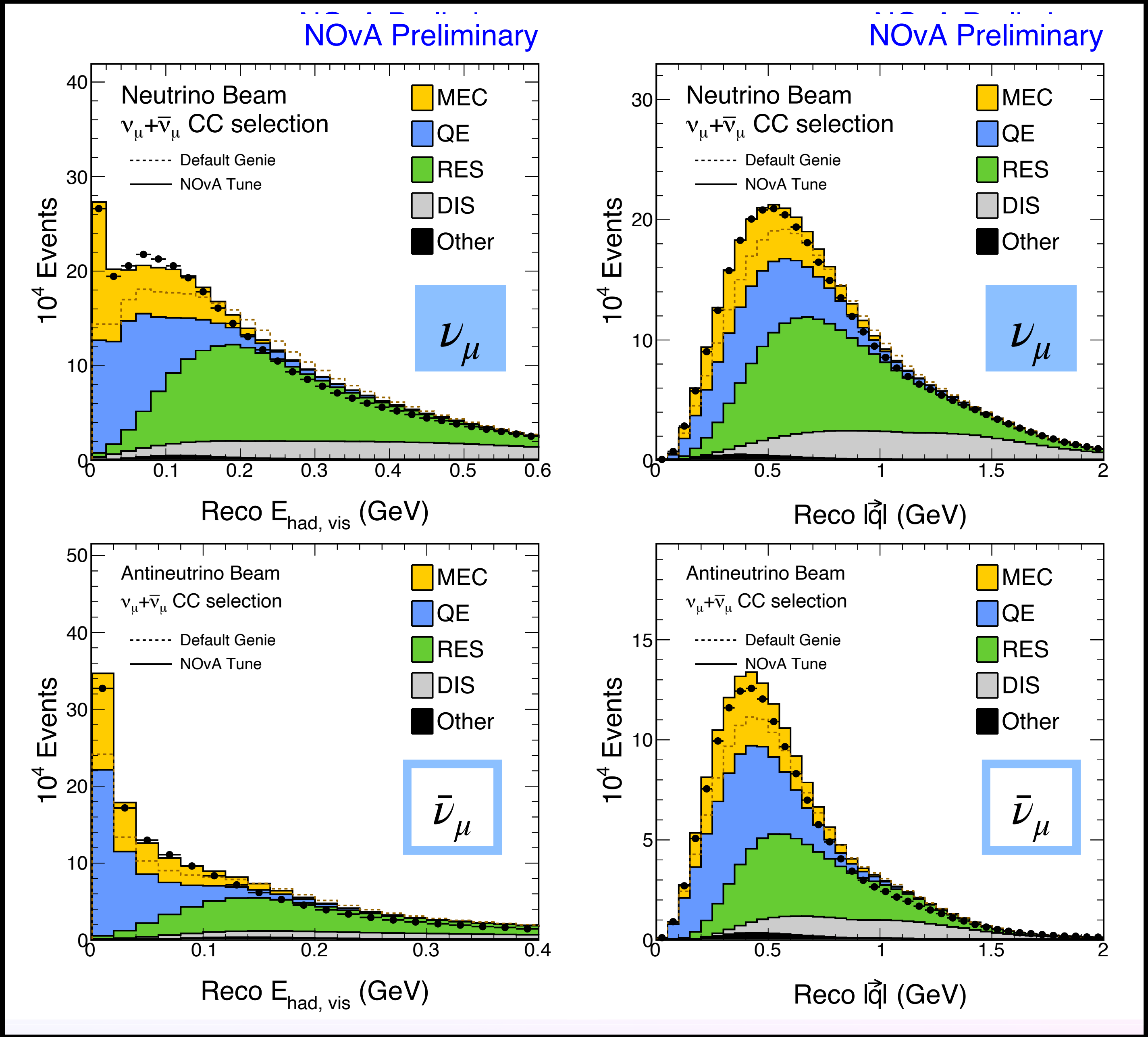
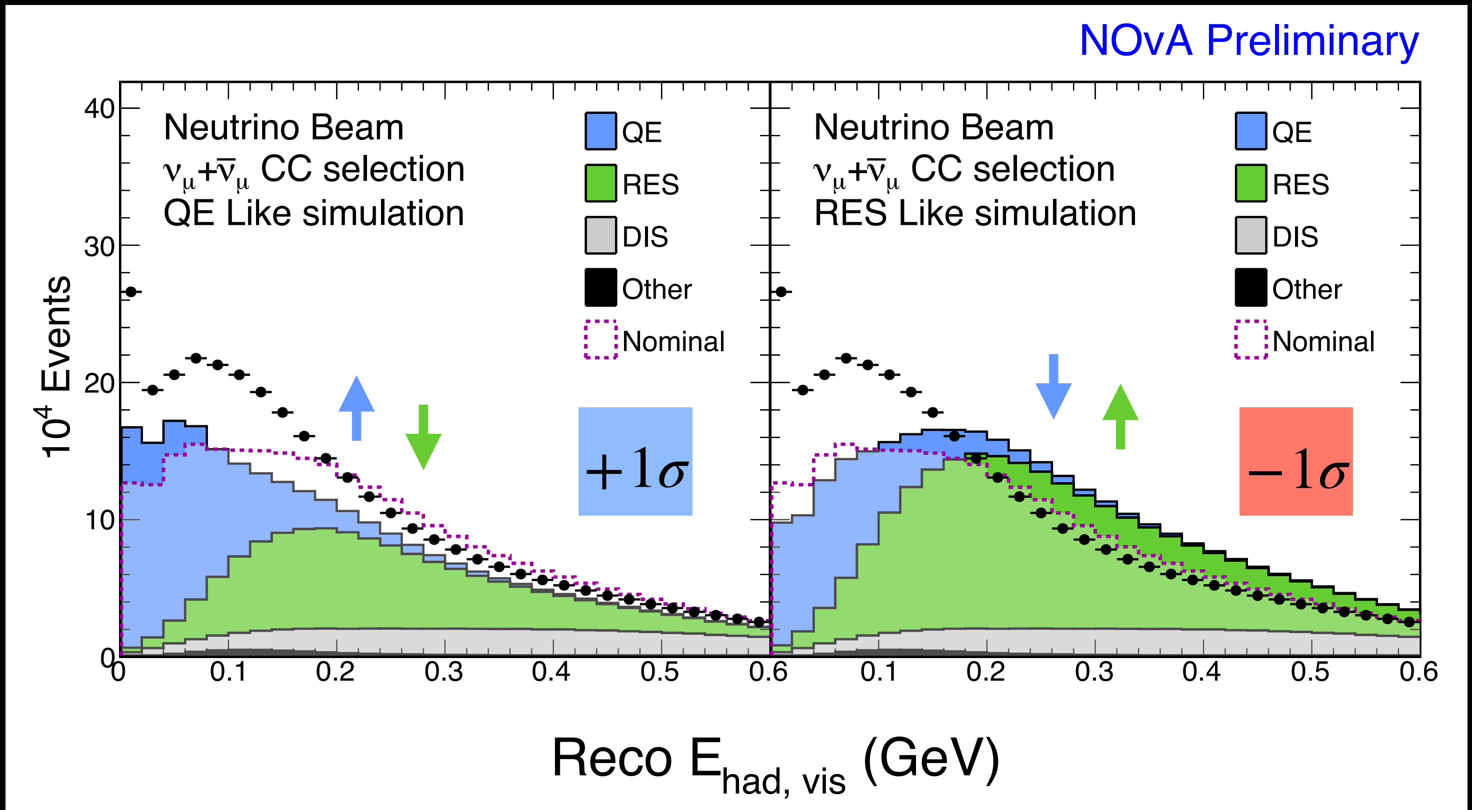


after the tune

MULTI-NUCLEON INTERACTIONS (2P2H) SYSTEMATIC UNCERTAINTIES

- The NOvA 2p2h or multi-nucleon interaction tune absorbs any other possible cross section model disagreement.
- We design an uncertainty that considers two alternate versions of 2p2h weights obtained from a QE-enhanced or RES-enhanced simulation.



QE-enhanced distorted simulation

RES-enhanced distorted simulation

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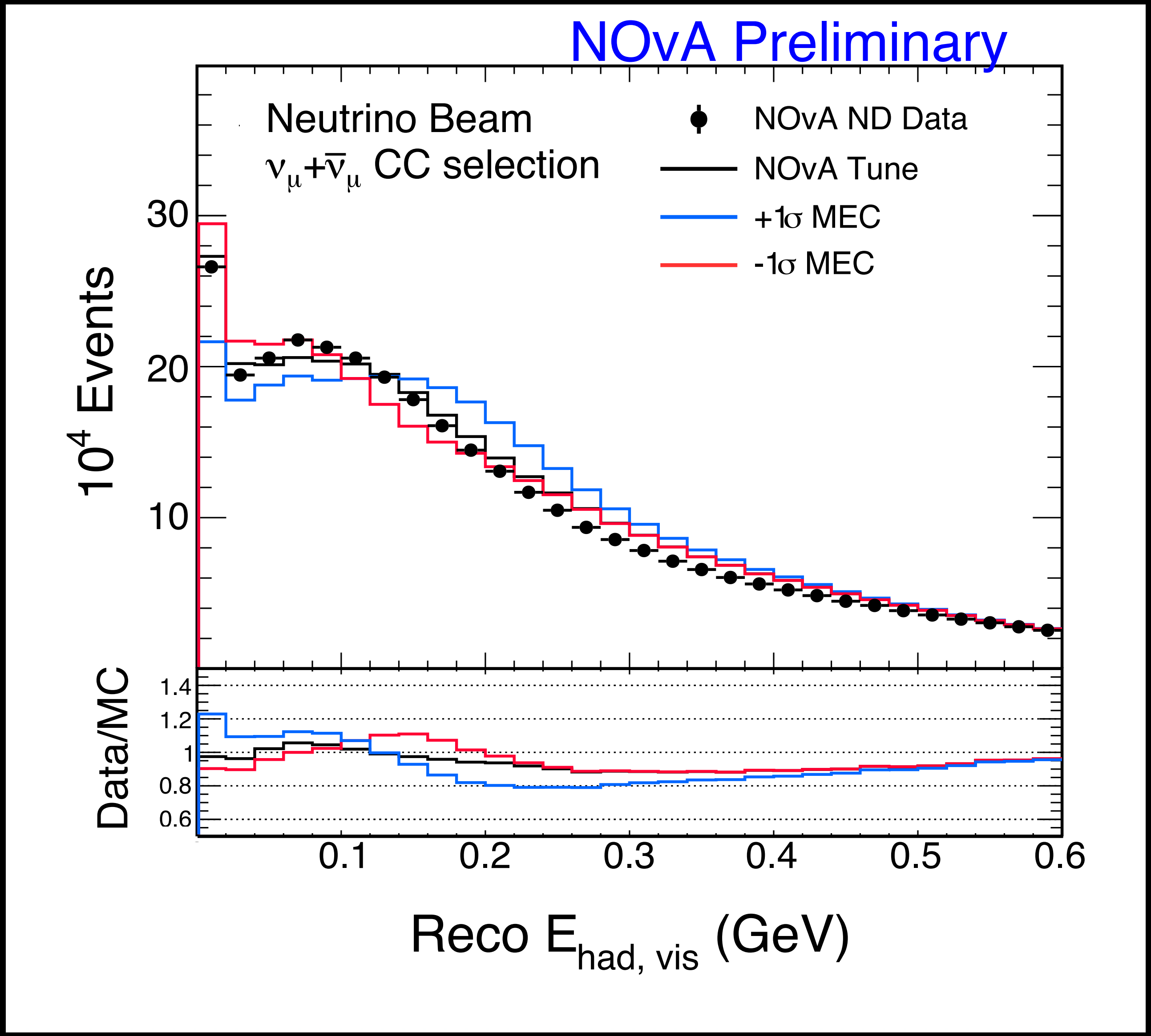
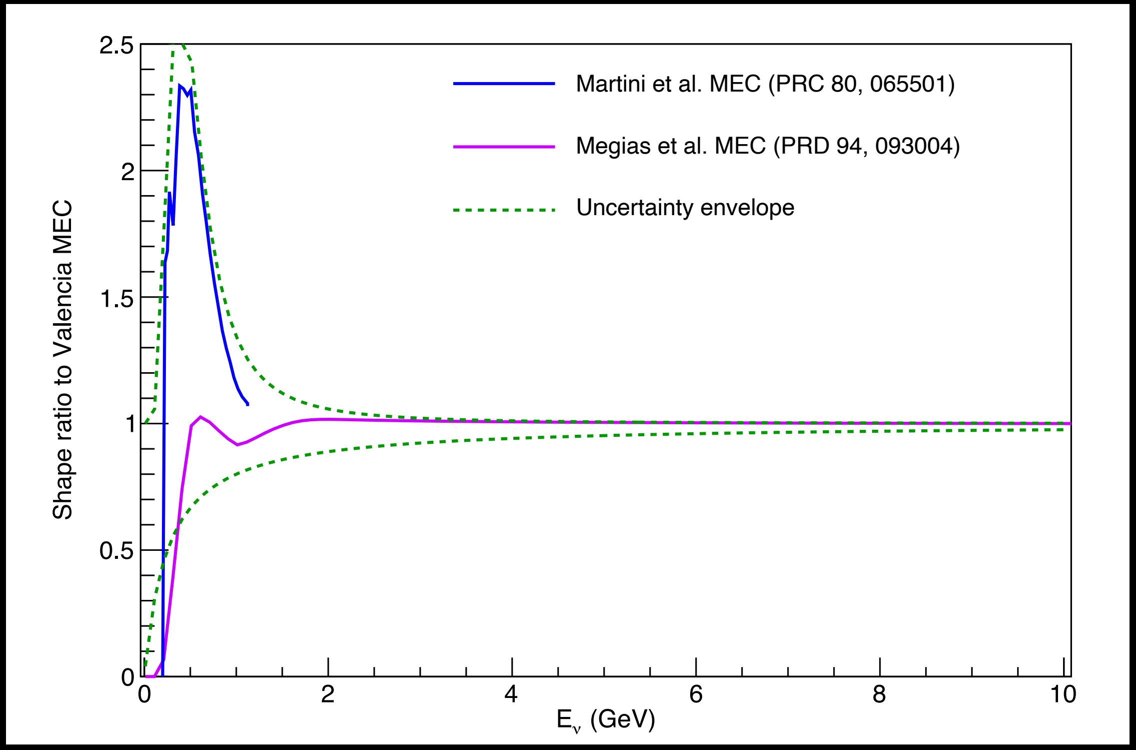


MULTI-NUCLEON INTERACTIONS (2P2H) SYSTEMATIC UNCERTAINTIES

- A few additional uncertainties are considered.
- A neutrino energy dependent normalization uncertainty parameterized as two functions that encapsulate the difference between Valencia MEC and alternate models.
- As well as a function to take into account the ratio of struck nucleon pairs.

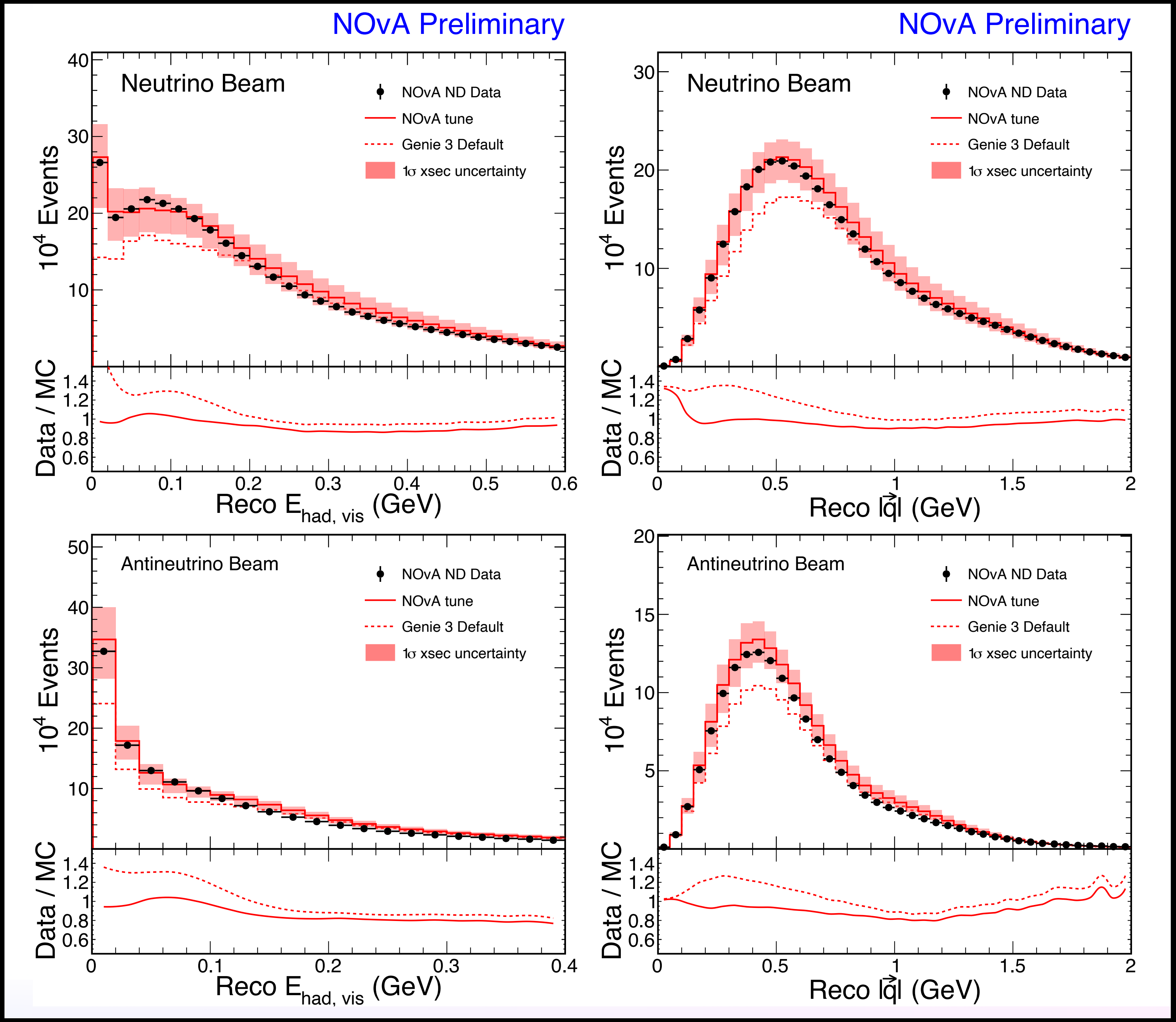


ν $$\frac{np}{np+nn} = 0.69 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases},$$

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

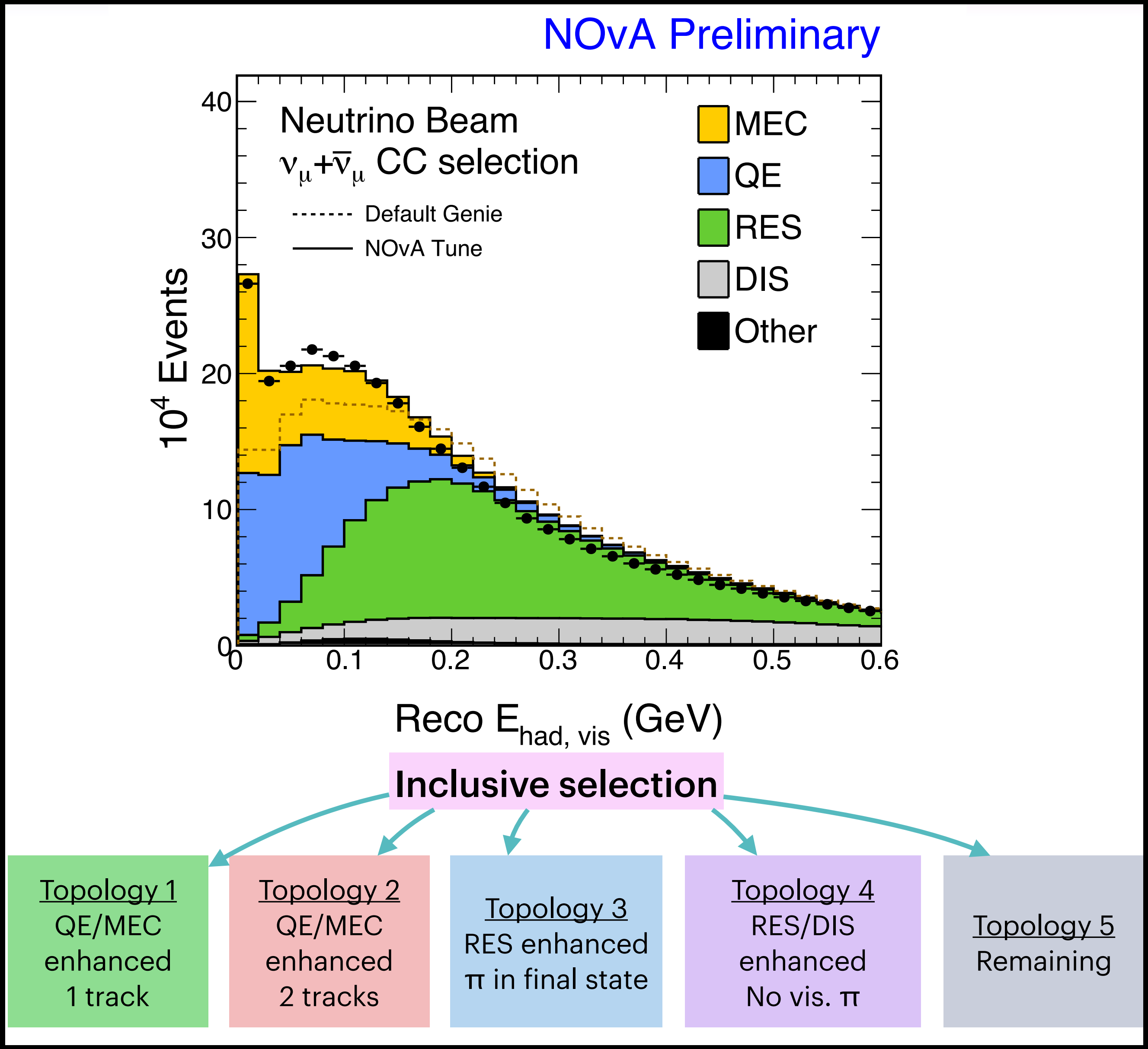
NEUTRINO INTERACTIONS IN NOVA

- Central value agreement is excellent after FSI and 2p2h adjustments.
- The uncertainty shown include GENIE uncertainties, FSI and custom 2p2h.
- The uncertainties account for the remaining differences with respect to the data.



NEUTRINO INTERACTIONS IN NOVA
WHAT IS NEXT?

- Near Detector neutrino data sets are high in statistics and rich in information which could constrain interaction model uncertainties, specifically from nuclear effects.
- Work is underway to subdivide it into topological categories that separate 2p2h/MEC from other channels.



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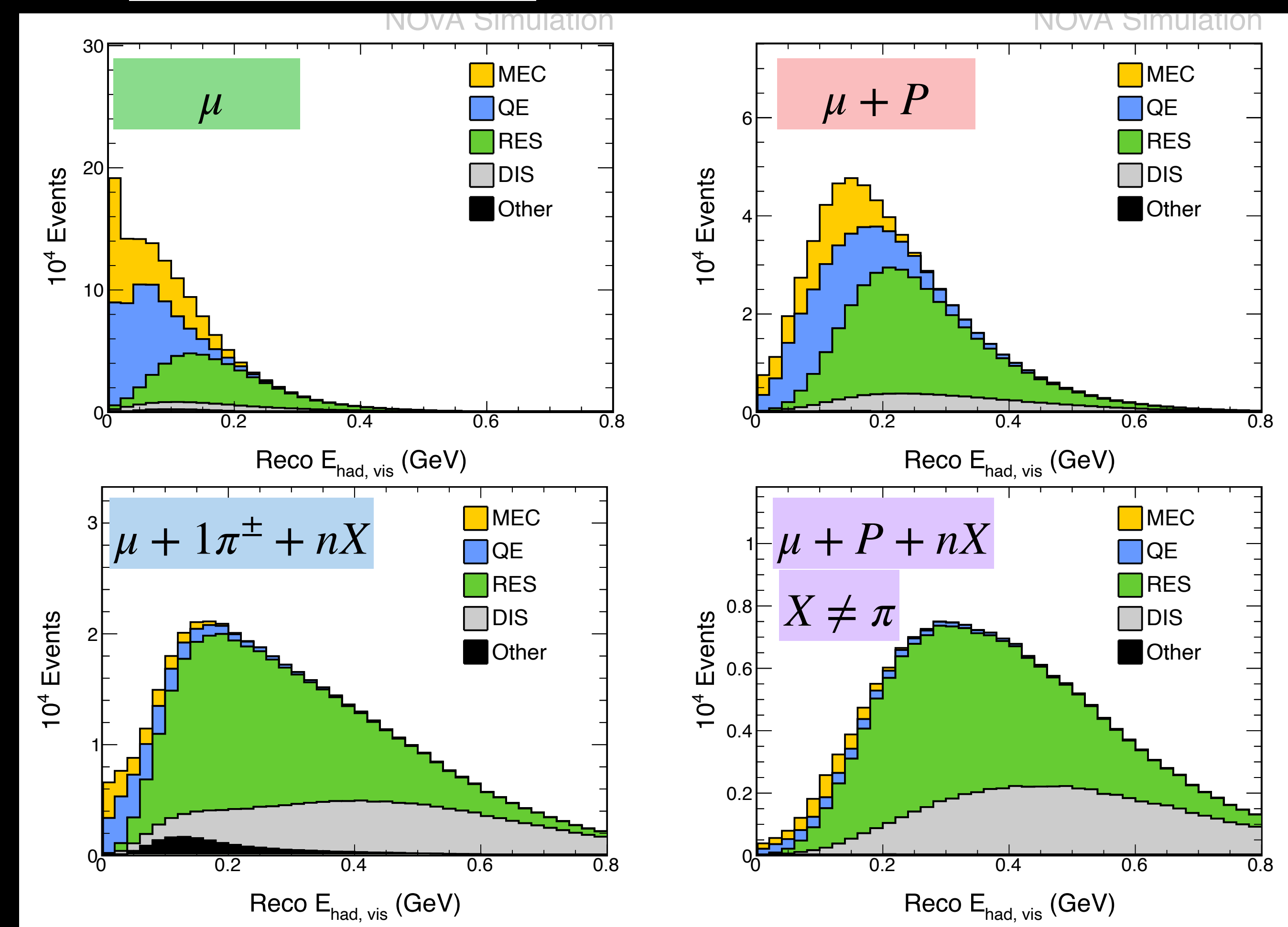
μ and **μ+P** samples contain mostly interactions without pions.



μ+π+X sample has a high purity of interactions with one charged pion.

μ+P+X contains a large fraction of interactions with multiple pions that are not visible.

SUMMARY

- Understanding of nuclear effects in neutrino oscillation experiments is crucial to the precision of these measurements.
- Neutrino oscillation experiments such as NOvA tackle nuclear effects by adjusting the models empirically masking some of the individual nuclear effects.
- Neutrino data sets at Near Detectors are close to infinite statistics and rich in information. Future work in sub-dividing these data sets could be interesting to distinguish more of the details of nuclear effects.
- Next generation of oscillation experiments will require modeling nuclear effects more accurately and knowledge of cross sections to a few percent for precision oscillation measurements.

Stay tuned!


NOVA COLLABORATION
DULUTH 2022