A Consideration of NOvA Cross Sections

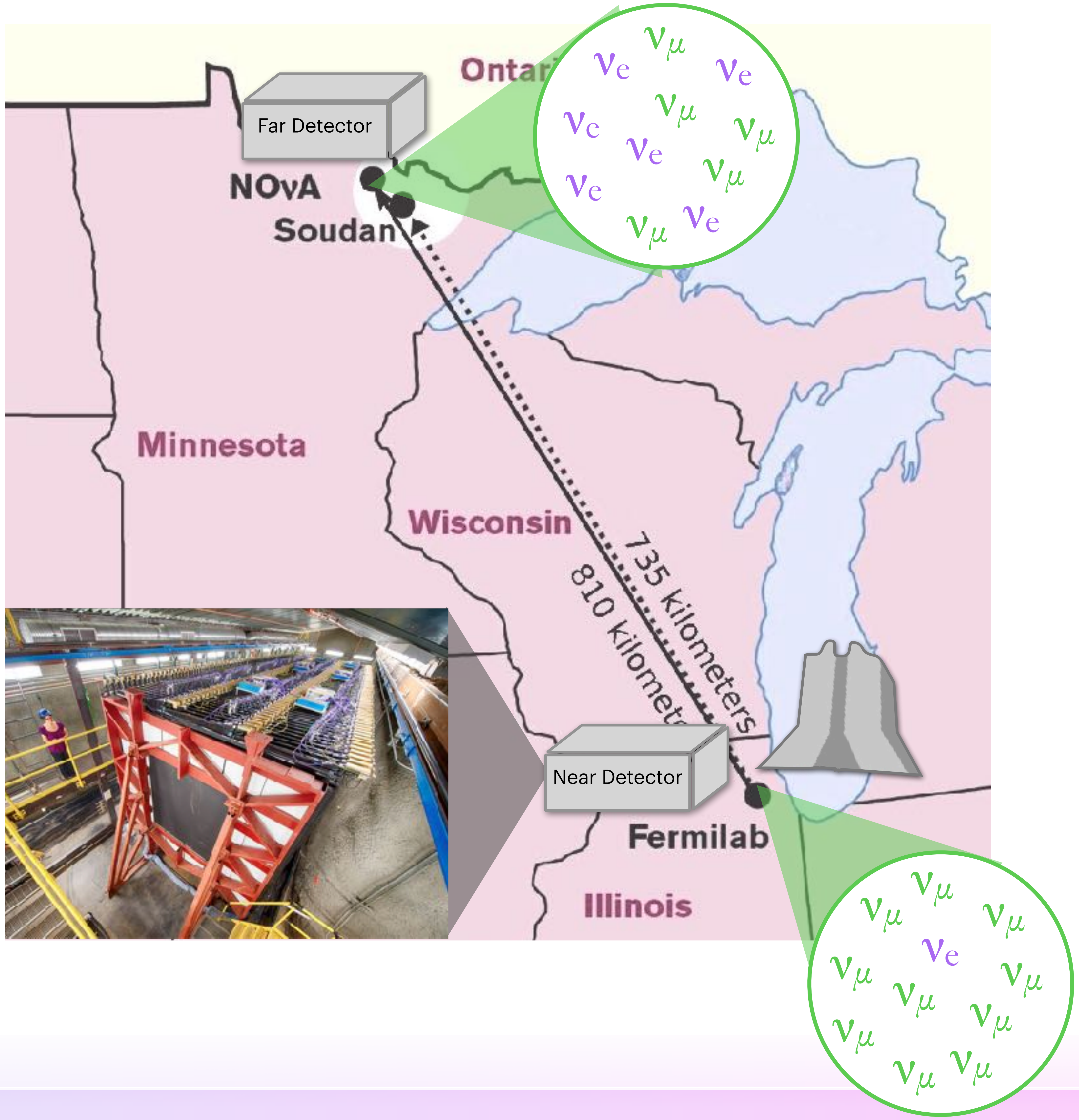
Maria Martinez-Casales

August 31, 2022
CIPANP 2022

NuMI Off-axis ν_e Appearance

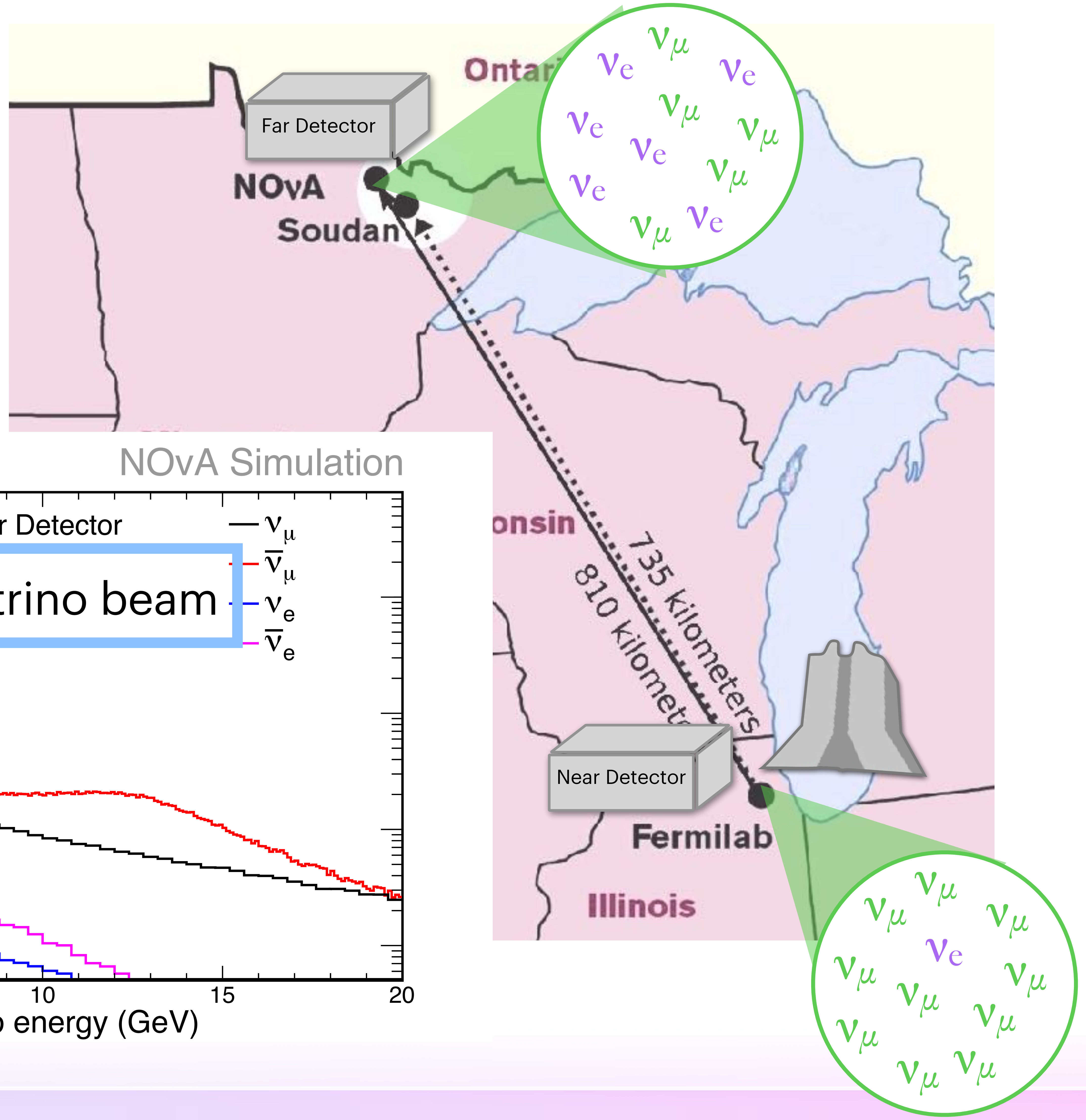
- Long-baseline neutrino experiment with Near Detector (ND) at Fermilab and a baseline of 810km.
- The main physics goal is measuring 3flavor neutrino oscillation parameters by observing ν_e appearance / $\nu_\mu$disappearance at the Far Detector (FD).

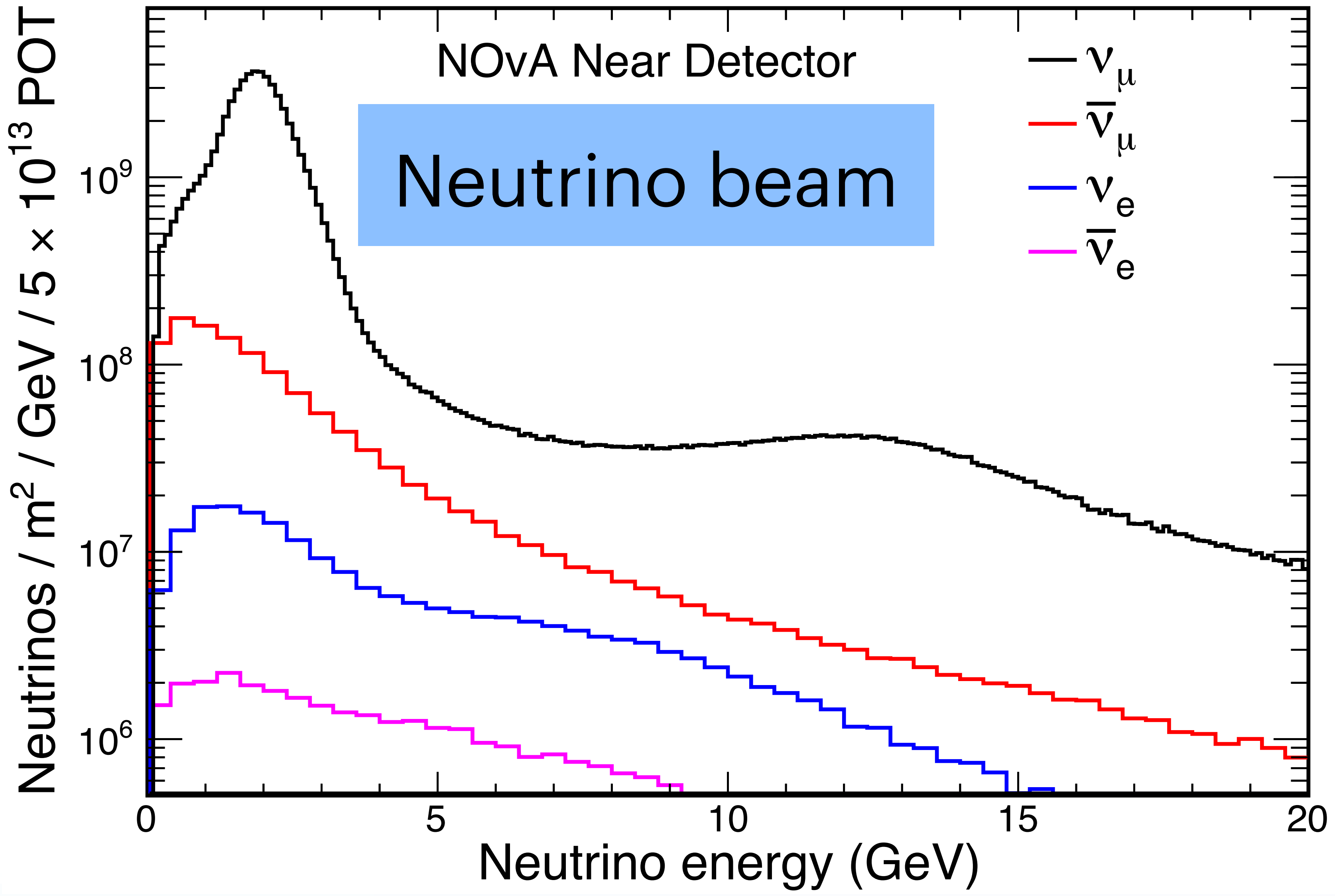
Yesterday's talk from
<u>Denver Whittington</u>

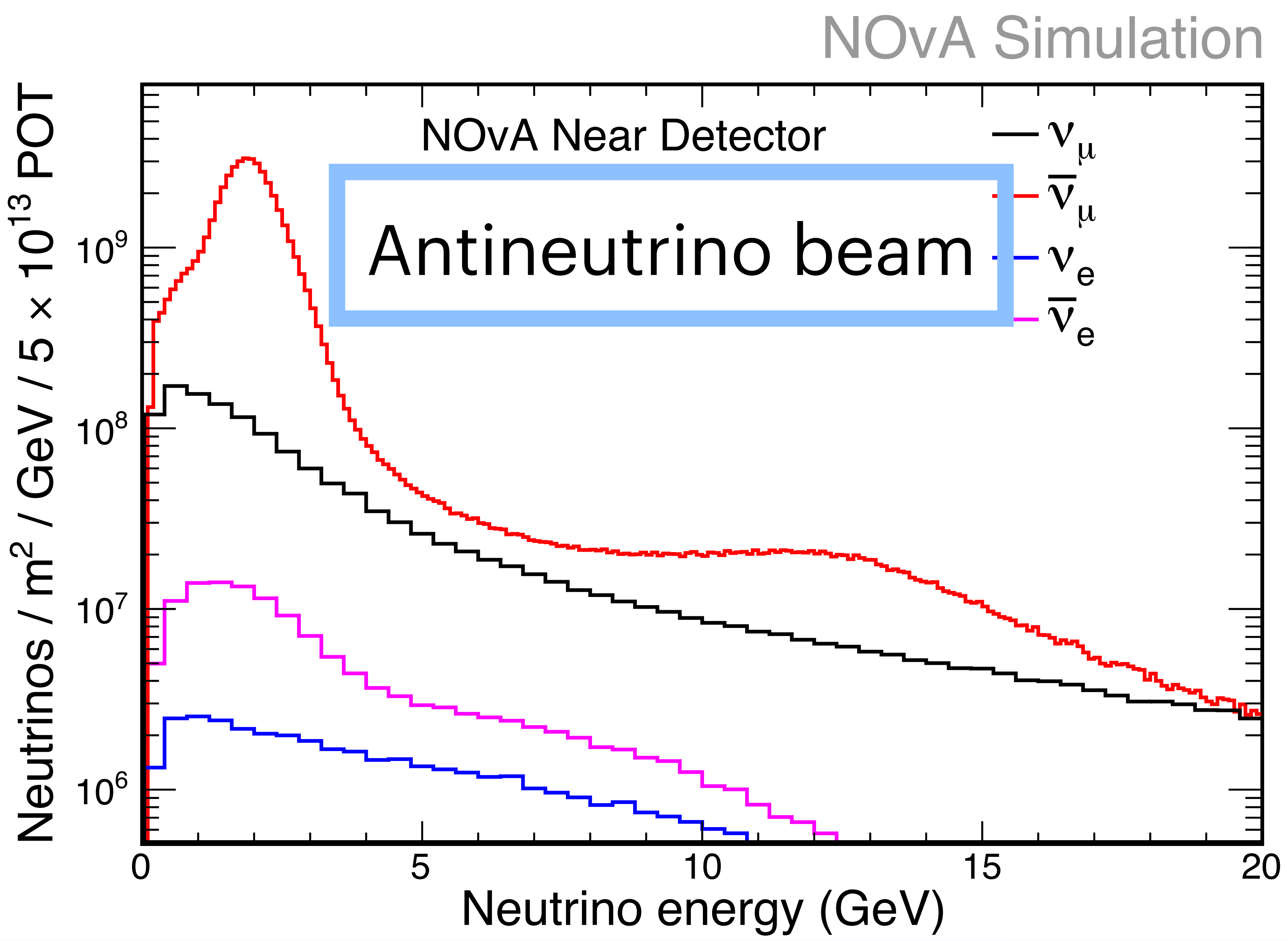


NuMI Off-axis ν_e Appearance

- The ND is 14.6 mrad off-axis from the NuMI beam
  - high intensity highly pure $\nu_\mu/\bar{\nu}_\mu$ beam
  - Peak at ~2GeV
- ND has collected a high stats dataset of $\nu_\mu/\bar{\nu}_\mu$ interactions
  - Measure neutrino cross sections (J. Hartnell NEUTRINO)
  - Constrain FD prediction







Predicting Far Detector Spectrum

- The extraction of oscillation parameters depends on neutrino energy reconstruction.
- The predicted energy spectrum in the FD is extrapolated from the ND spectrum depending on our understanding and modeling of:
    - Neutrino flux
    - Neutrino cross sections
    - Detector response

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

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

Extract oscillation parameters

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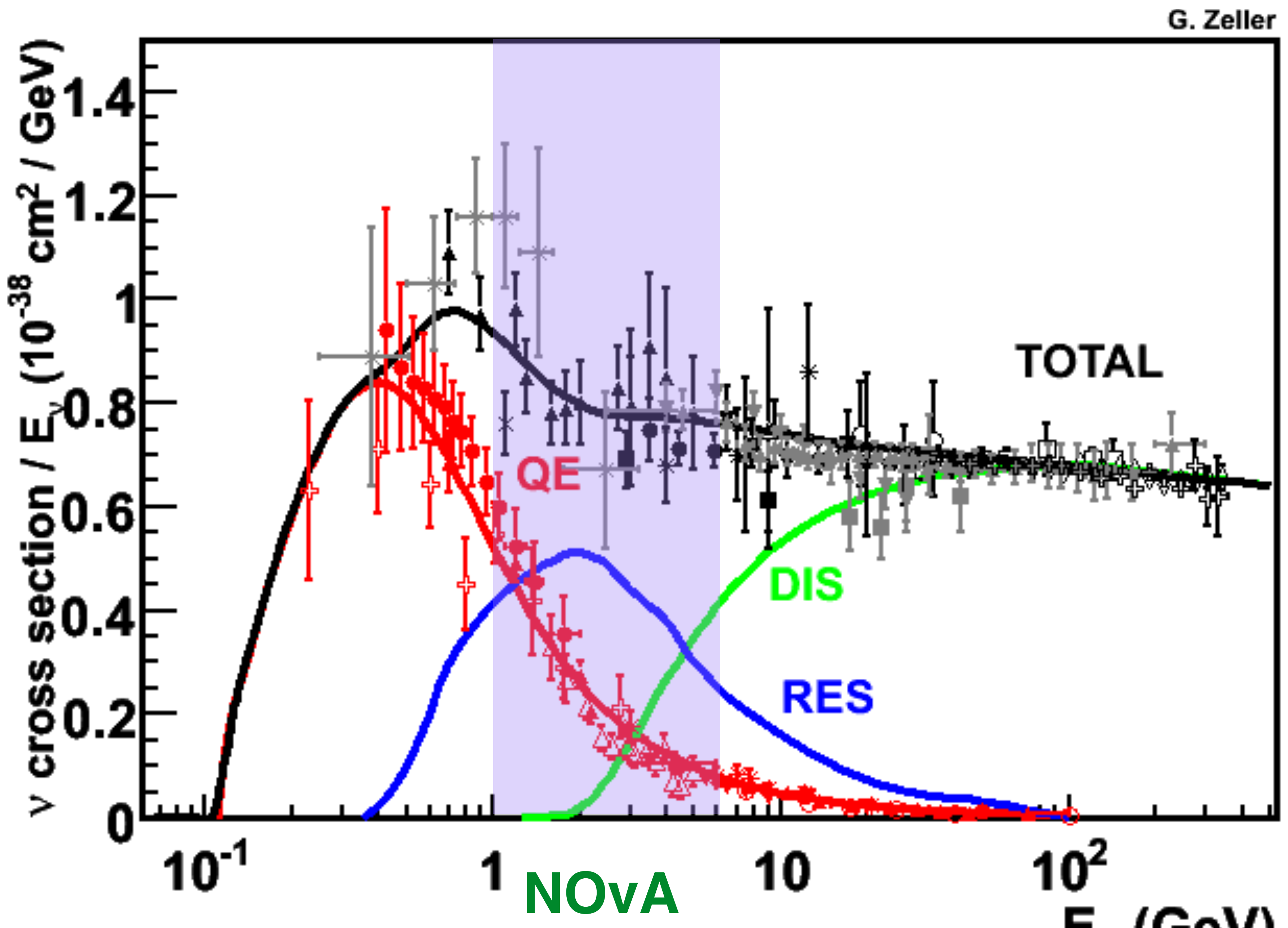

J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

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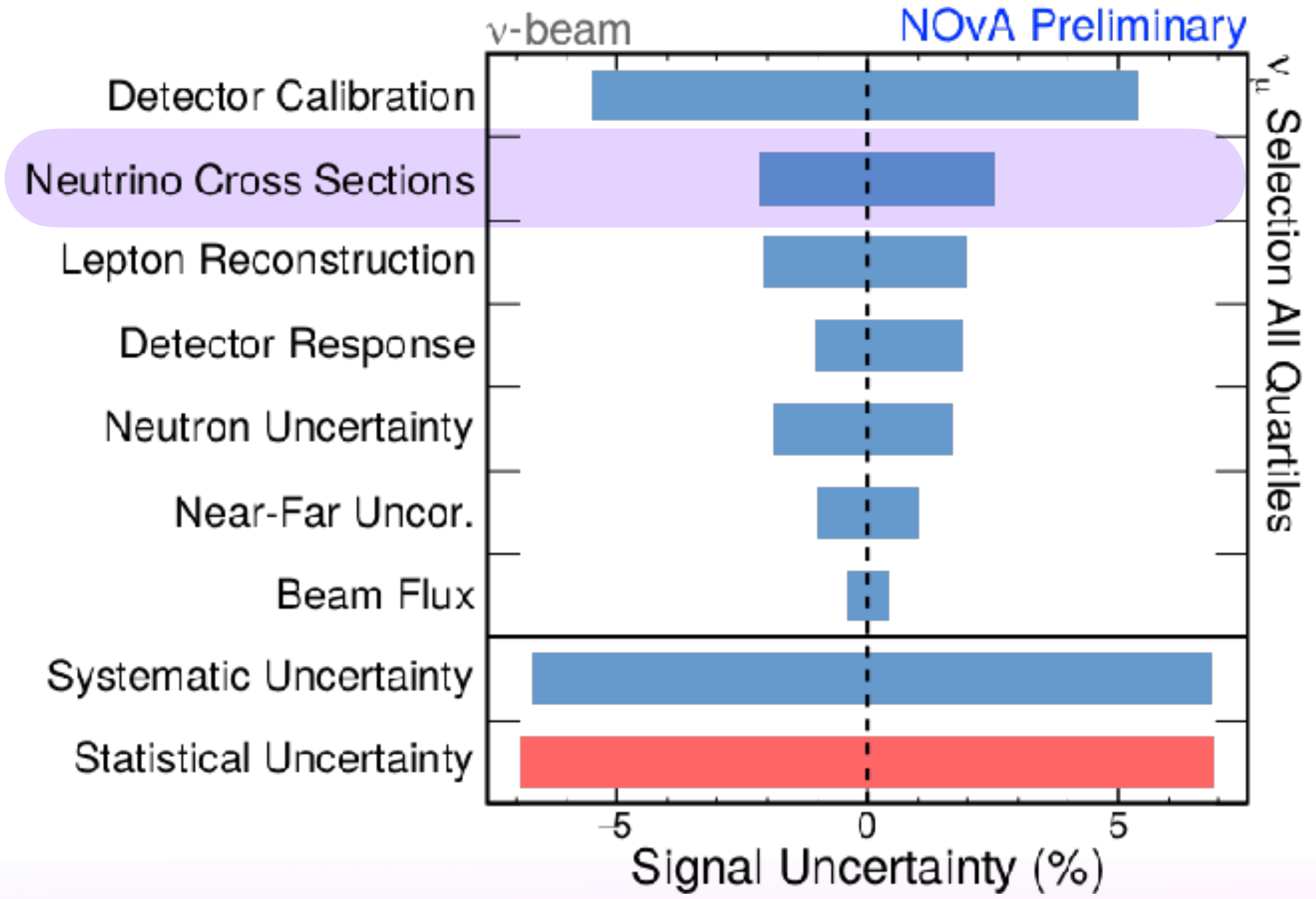


Neutrino interactions

- Neutrino interactions are simulated using the GENIE v3.0.6

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GENIE N1810j_00000

ν - free nucleon interactions

Quasi-Elastic (QE)
Valencia 1p1h
Z-expansion axial form factor
arXiv:1102.2777

Resonance (RES)
Berger-Sehgal
arXiv:0709.4378

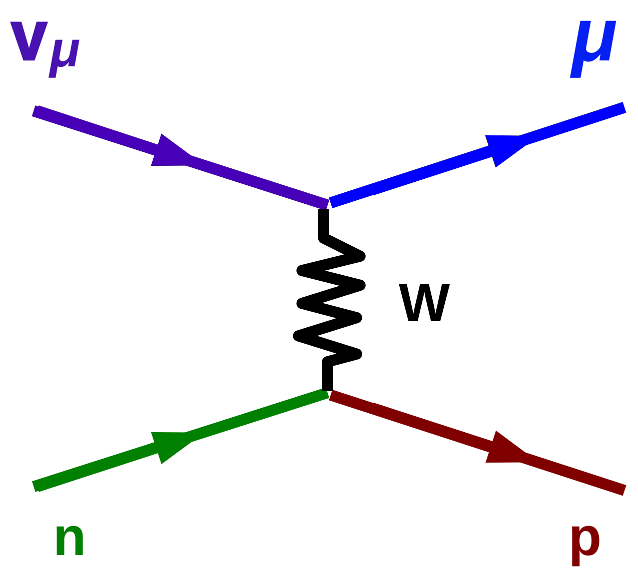
Deep Inelastic Scattering (DIS)
Bodek-Yang
arXiv:1012.0261

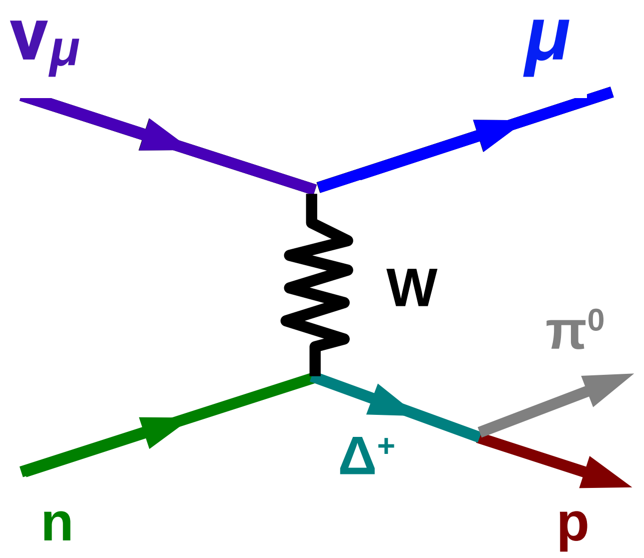
Multinucleon interactions

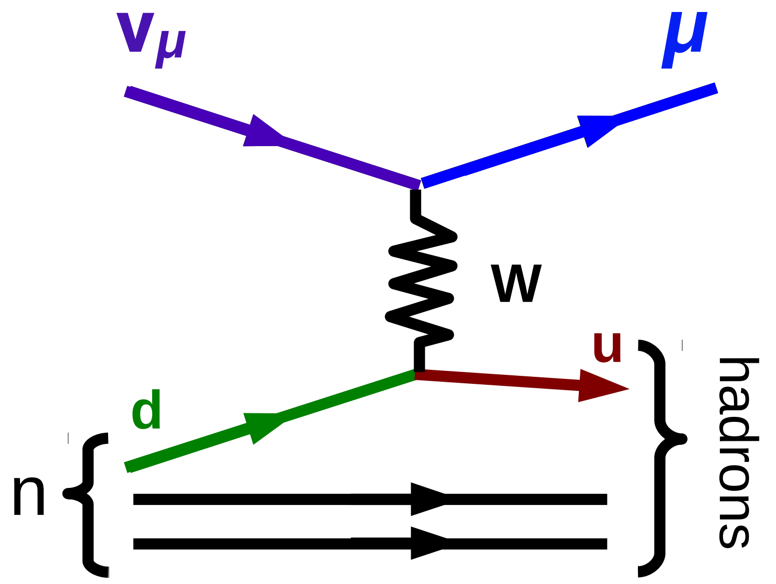
Meson Exchange Current (MEC/2p2h)
Valencia 2p2h
arXiv:1102.2777

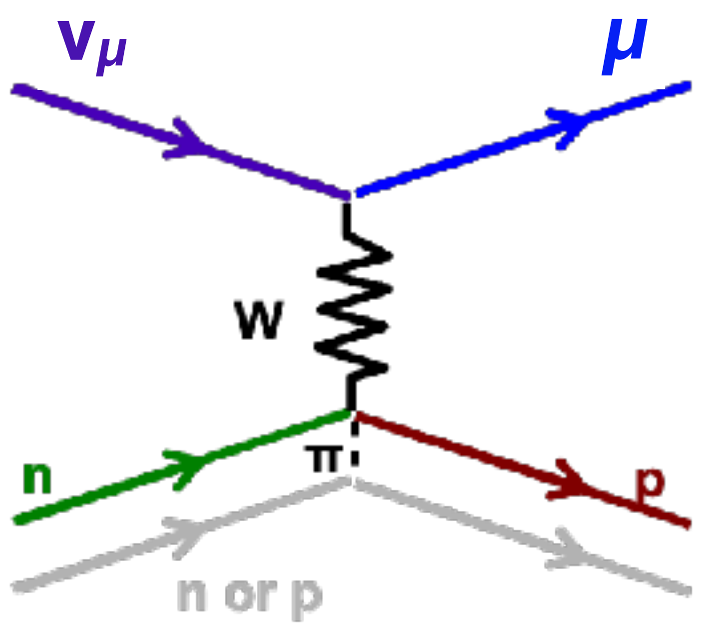
Interactions with the nuclear environment

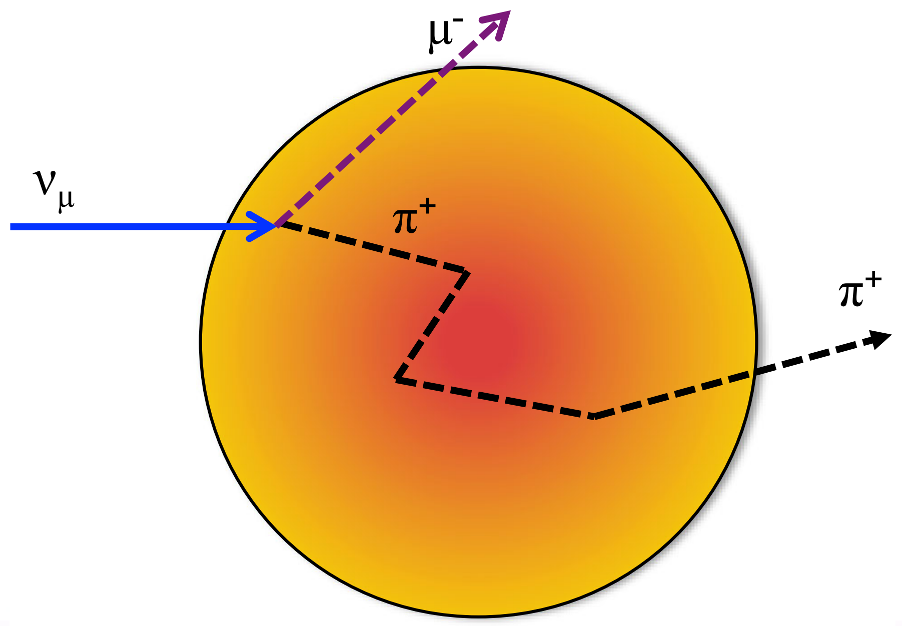
Final State Interactions (FSI)
hN Semi Classical Cascade
doi.org/10.1063/1.3274190











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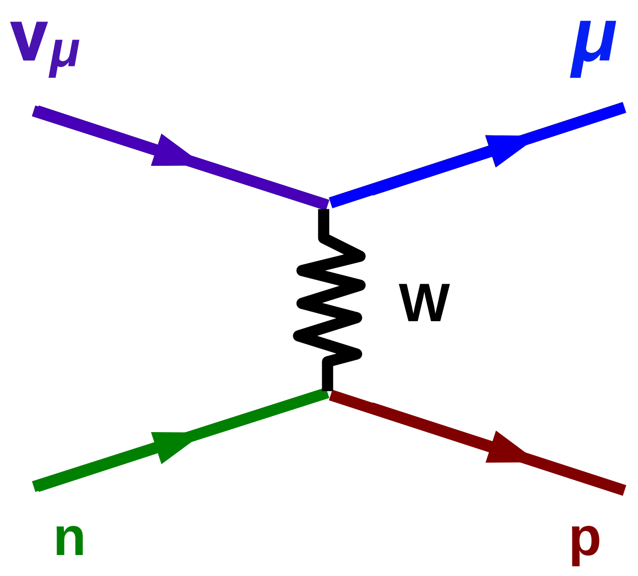
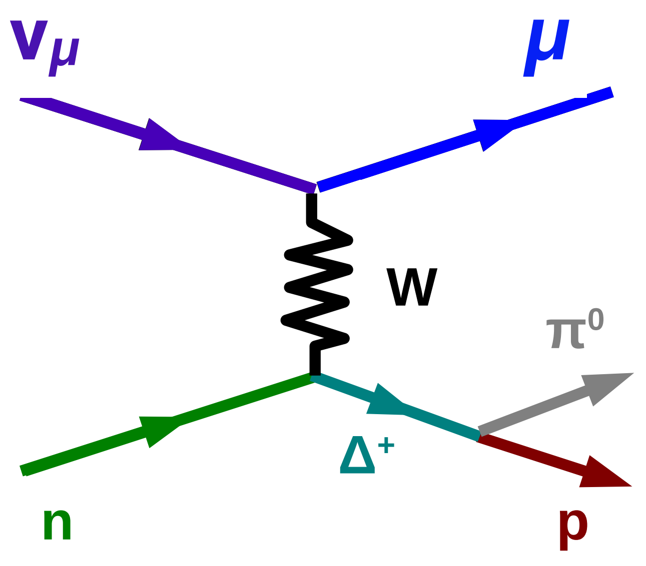
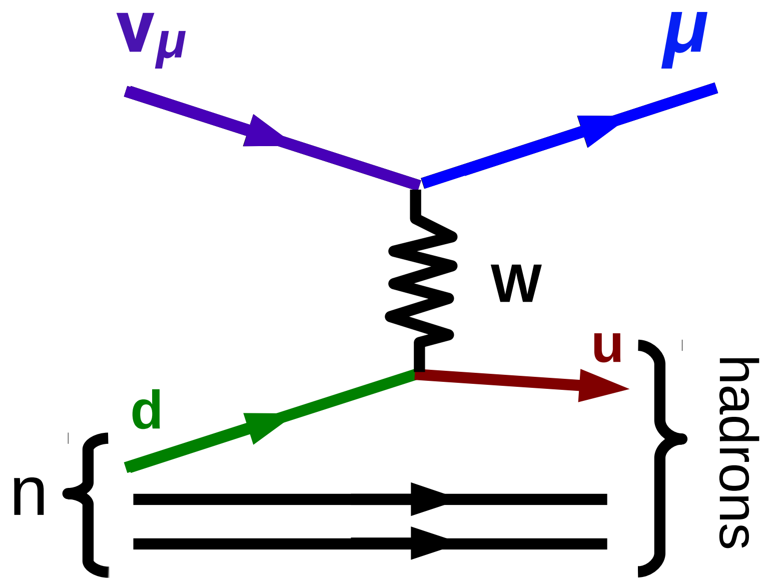




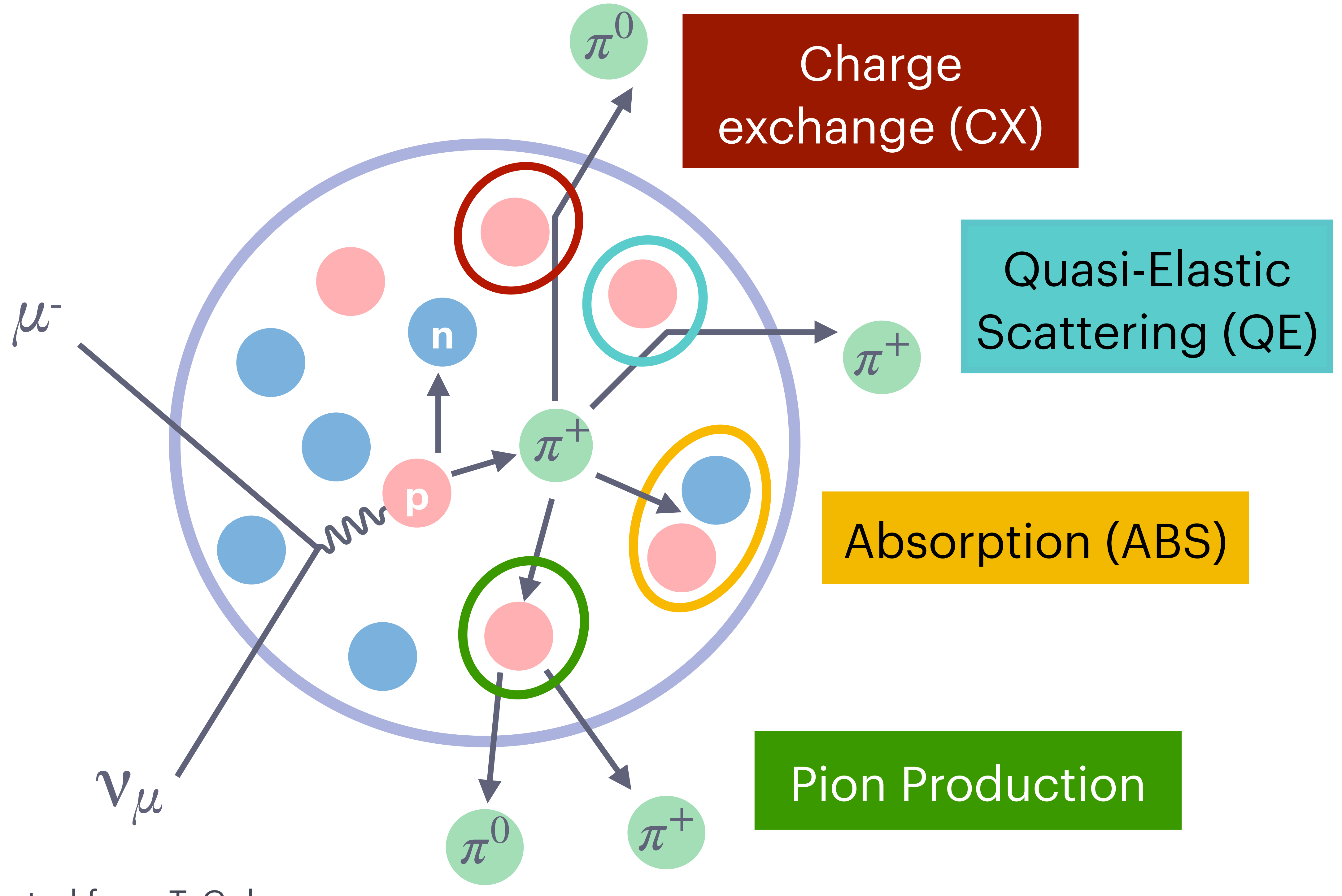


Custom adjustment to NOvA ND data.

Fit to external pion scattering data.

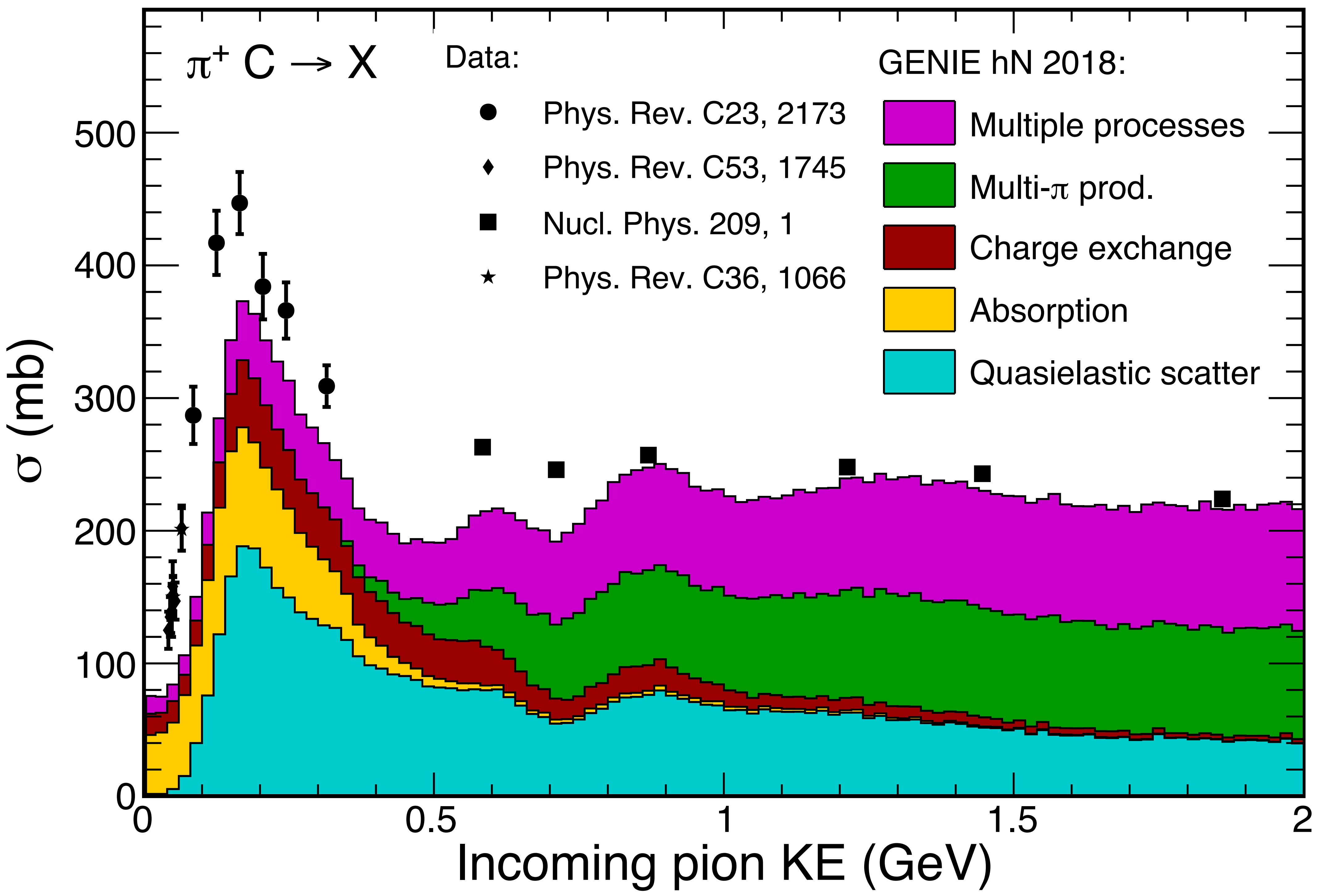
Final State Interactions

- Nucleons and pions reinteract when propagated through the nucleus.
- For 2020 oscillation results, we used the hN2018 semi-classical cascade FSI model in GENIE 3.0.6.



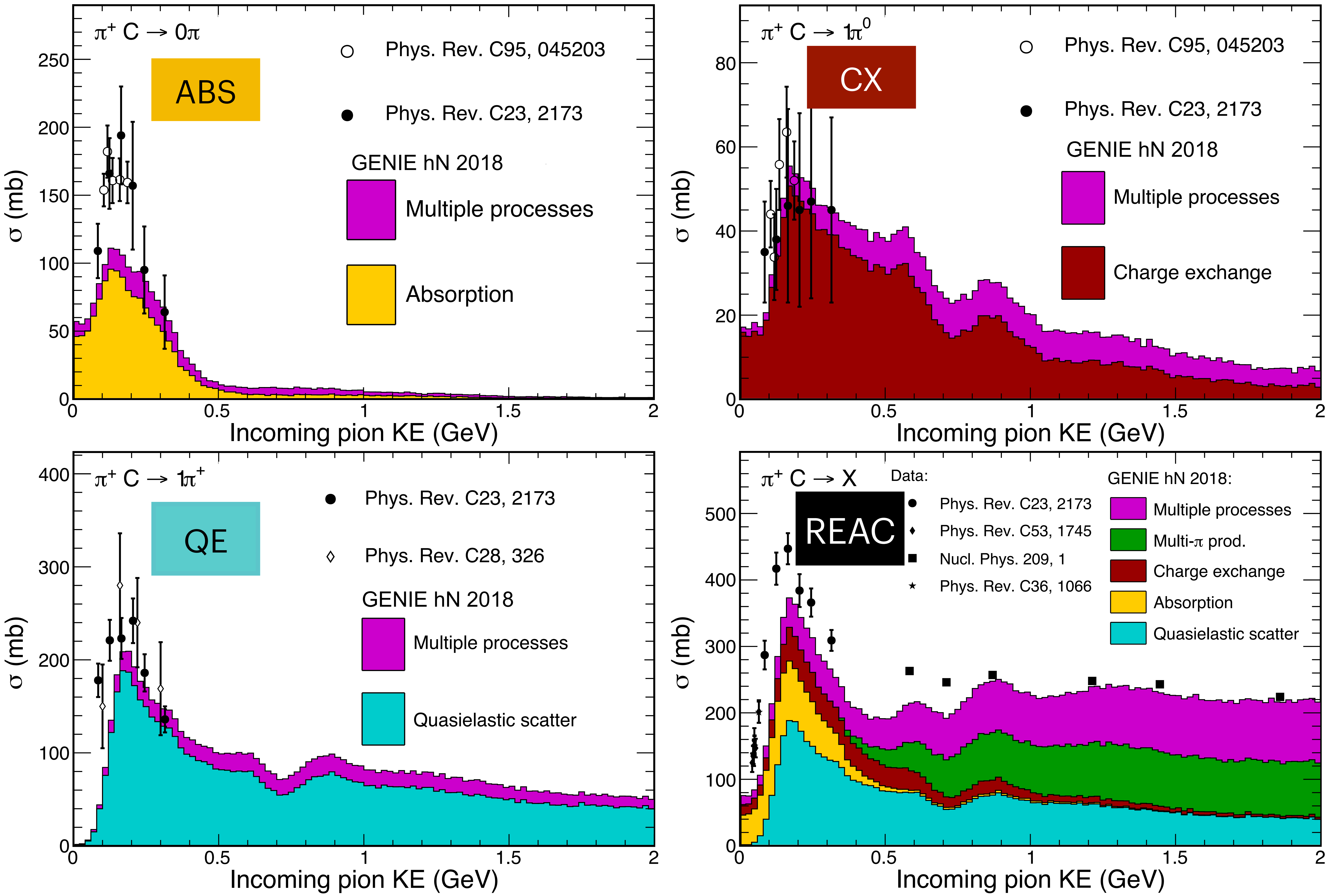
Adapted from T. Golan

- Pion scattering data is categorized into the topological channels based on the outgoing particles.
- Agreement with ^{12}C data is poor.



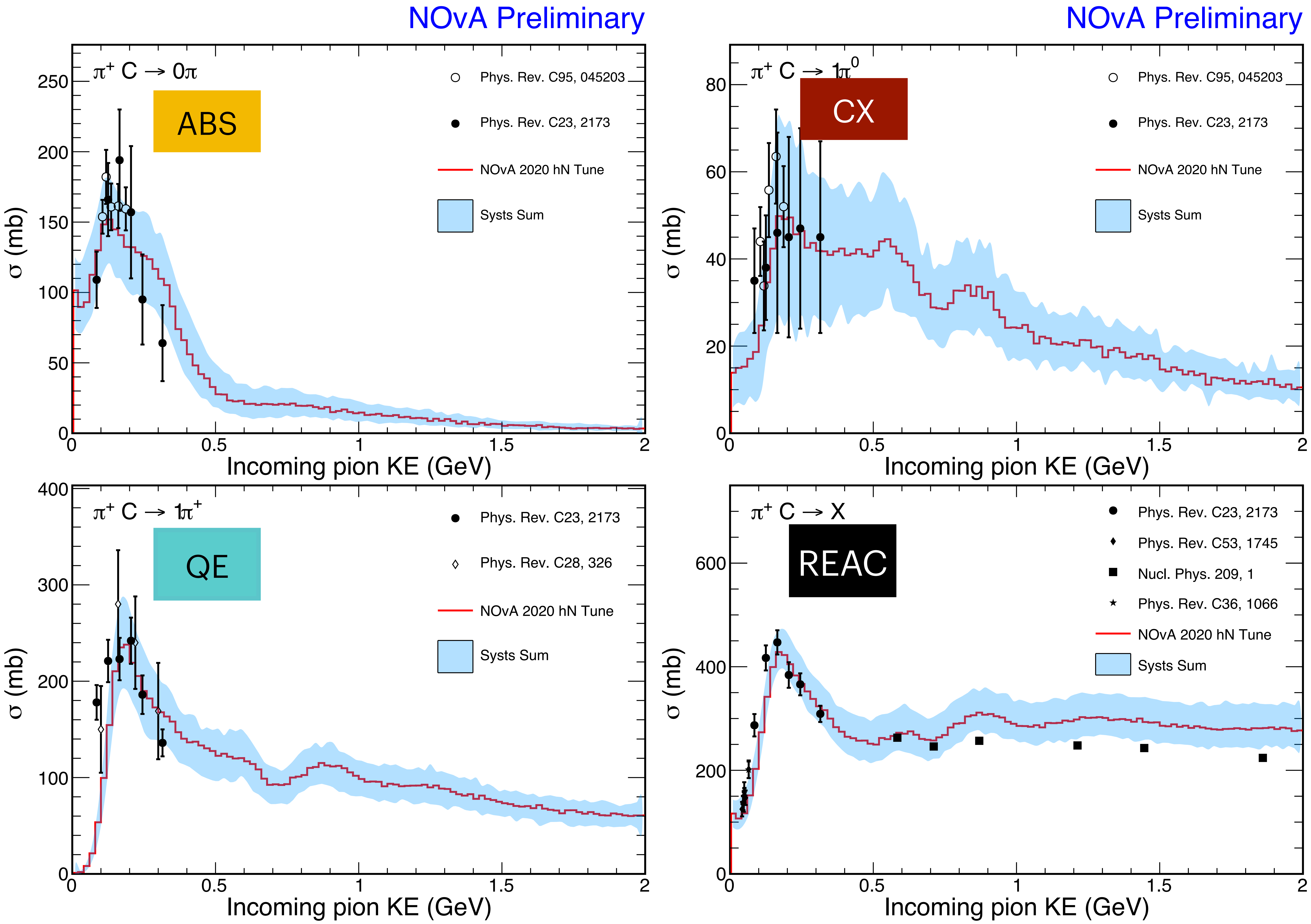
Final State Interactions

- Total "reactive" cross section
  - REAC = ABS + CX + QE + other processes
- Adjustments:
  - "fate fractions" for these 3 channels
  - Mean Free Path (MFP), which scales inversely with cross section.



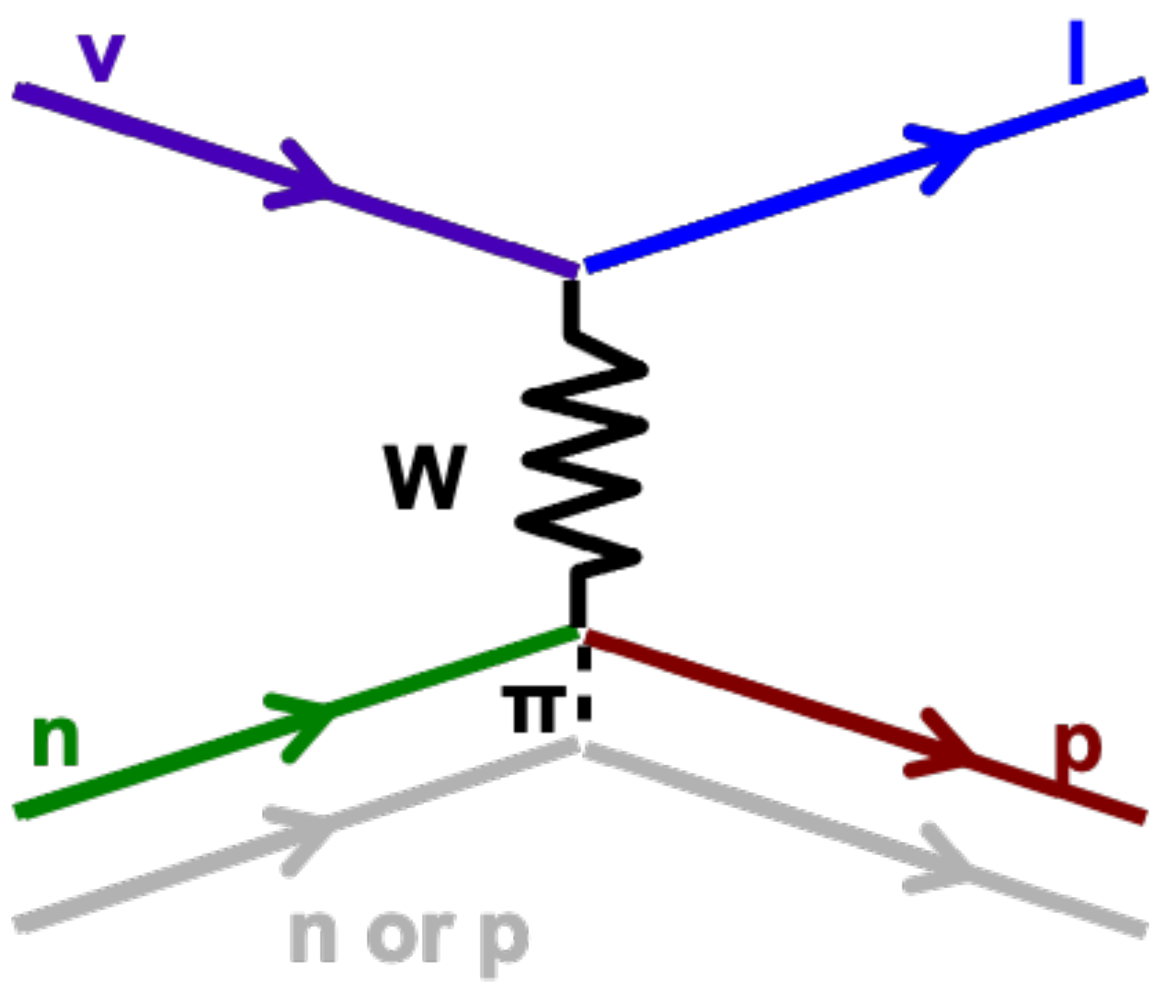
Adjusted FSI and uncertainties

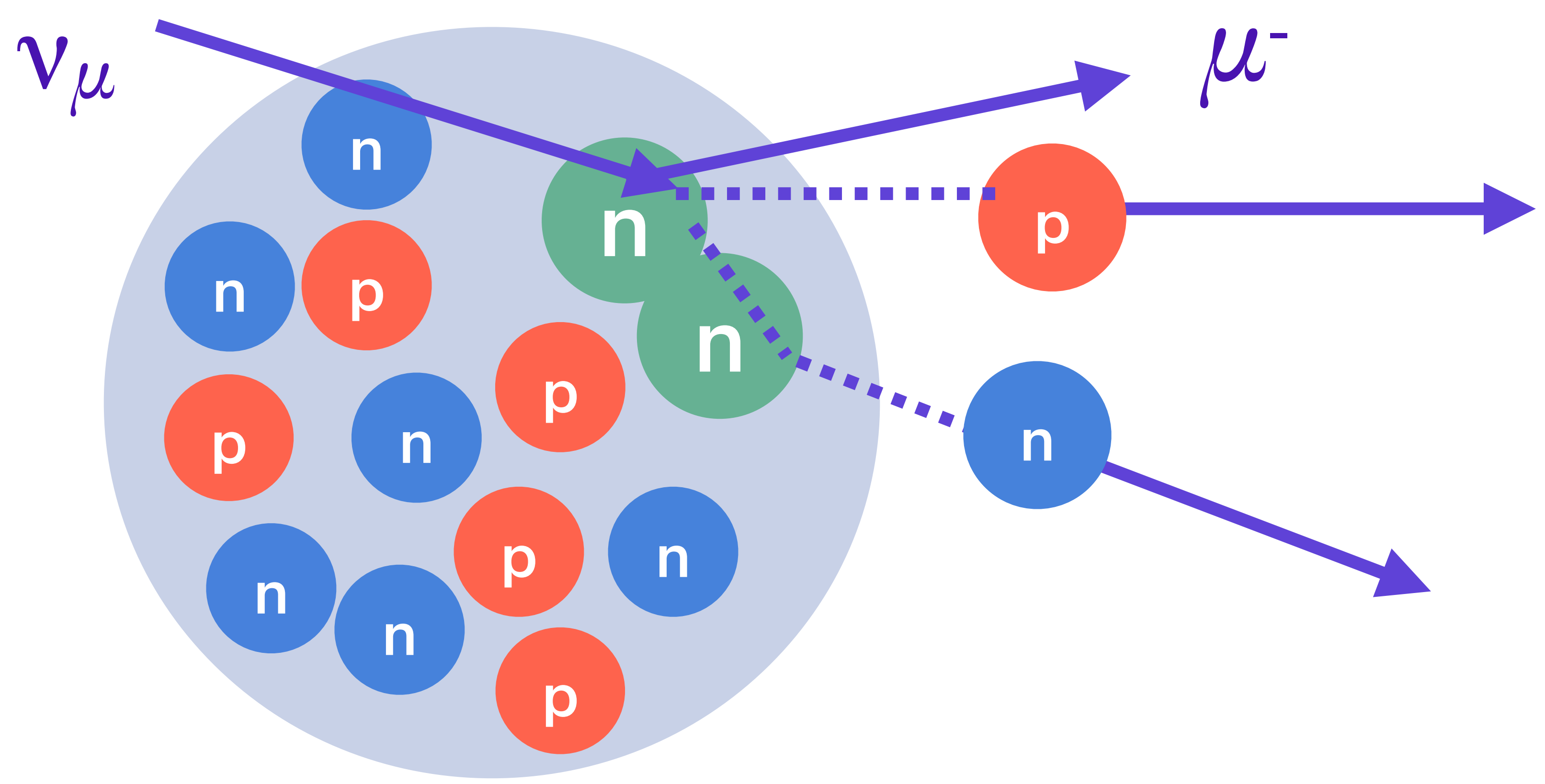
- After the tuning, four uncorrelated uncertainties are constructed.
- Three uncorrelated uncertainties of the “fate fractions”.
- The MFP uncertainty is constructed with the values of this parameter that bracket the external data.



Multi-nucleon interactions

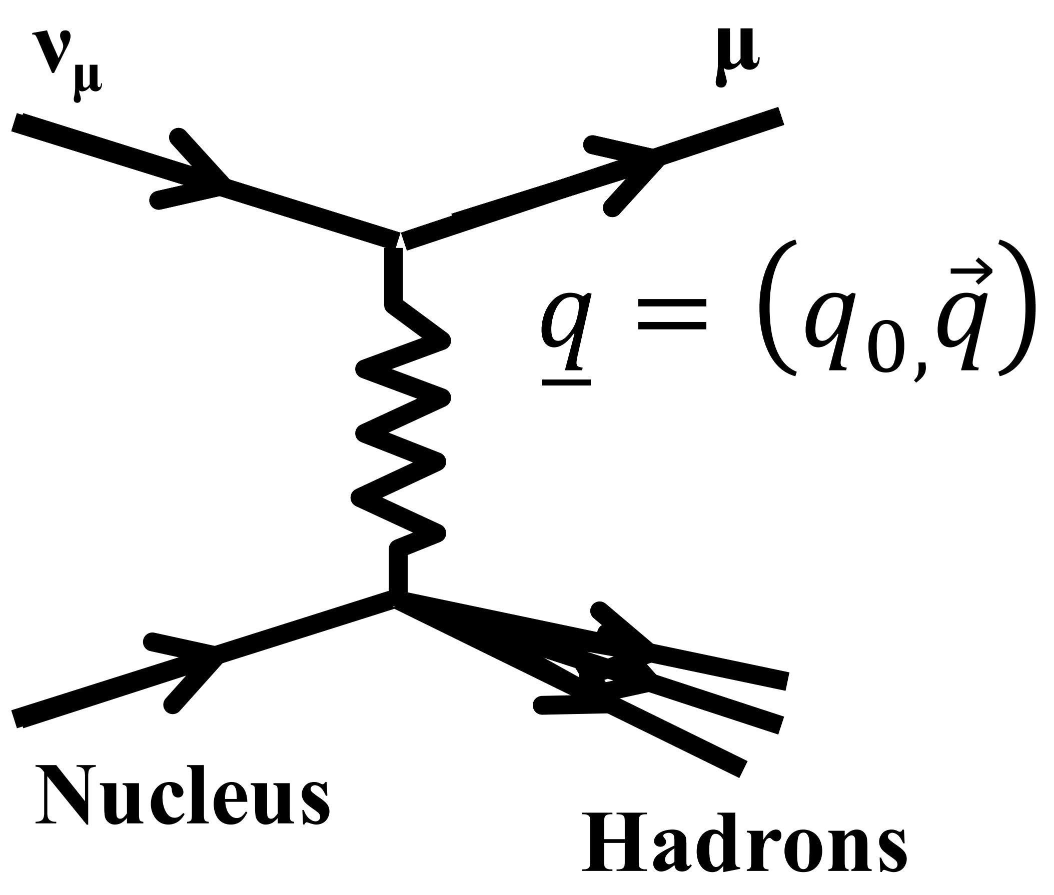
- Binding between a nucleon pair can occur via exchange of virtual mesons. Nucleons inside the nuclei form correlated pairs. ν scattering knocks out the pair.
- This interaction type is not fully understood and no model correctly predicts the observed data at the Near Detector
  - We adjust Valencia MEC to NOvA ND data
- Adjustment reshapes MEC kinematics to match data, effectively adding missing processes (like short range correlations between nucleons), so we call it **NOvA 2p2h**.

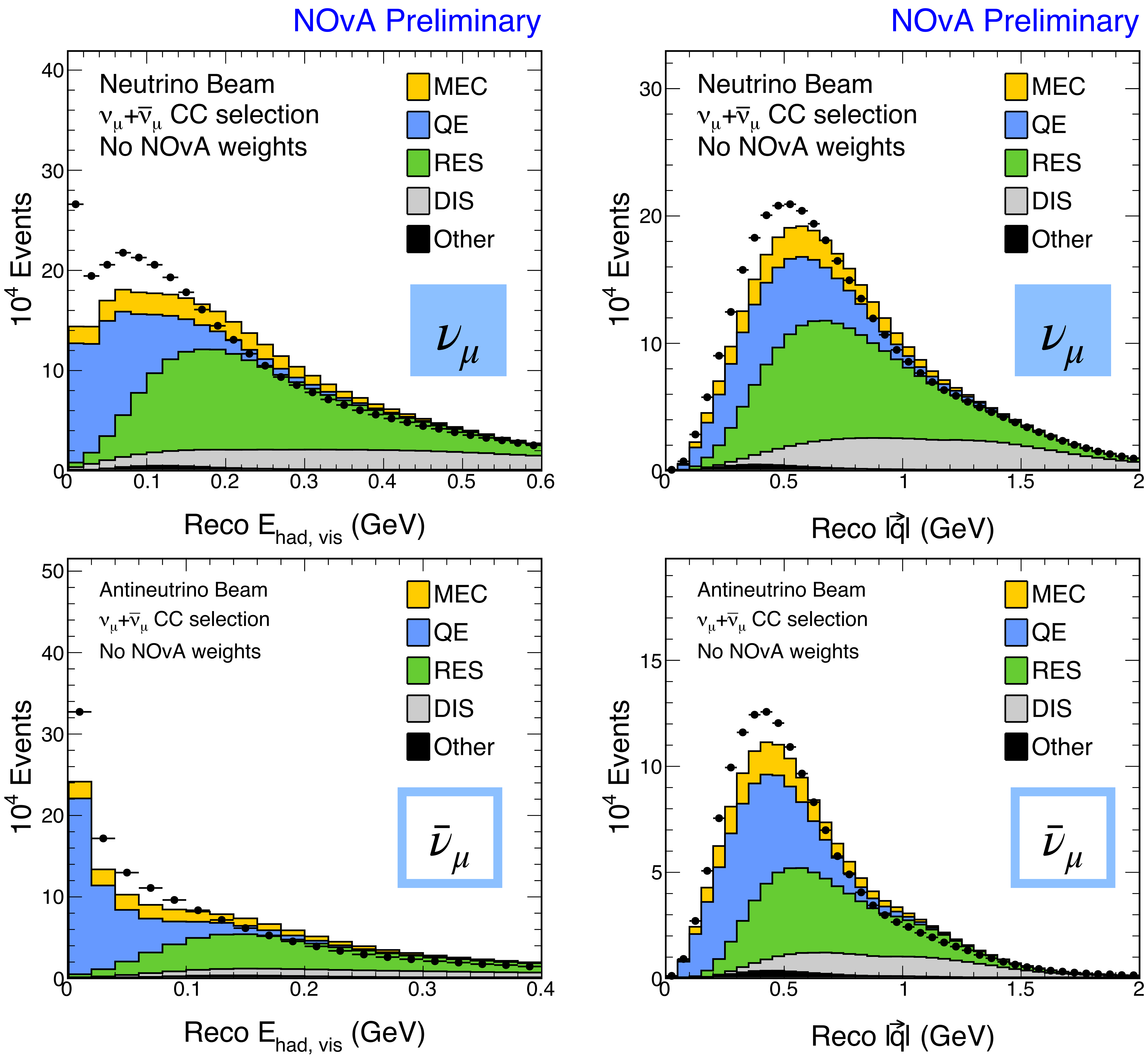




Adjustment of 2p2h interactions

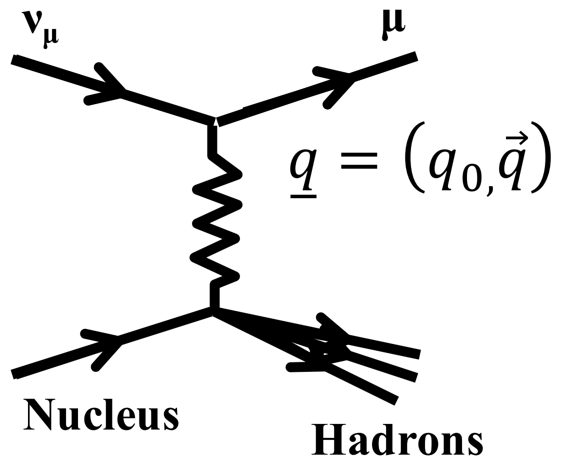
- Projections on the reconstructed q_0 and $|q|$ axes before MEC adjustment.
- Colors represent the interaction types.



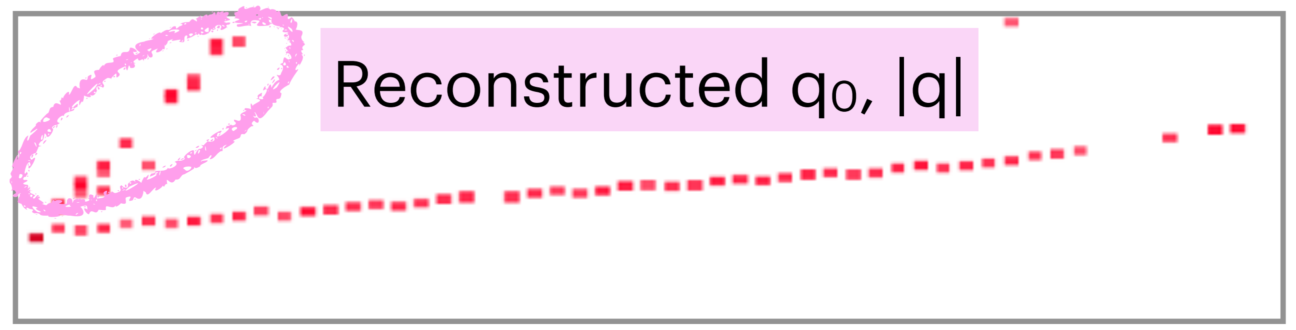


Adjustment of 2p2h interactions

- Weights are parametrized as two 2D gaussians and normalization of the base model.
- 13 parameters fitted by minimizing χ^2 of neutrino data and simulation.
- The same weights are used for neutrino and antineutrino beam simulation resulting in good agreement with data for both.

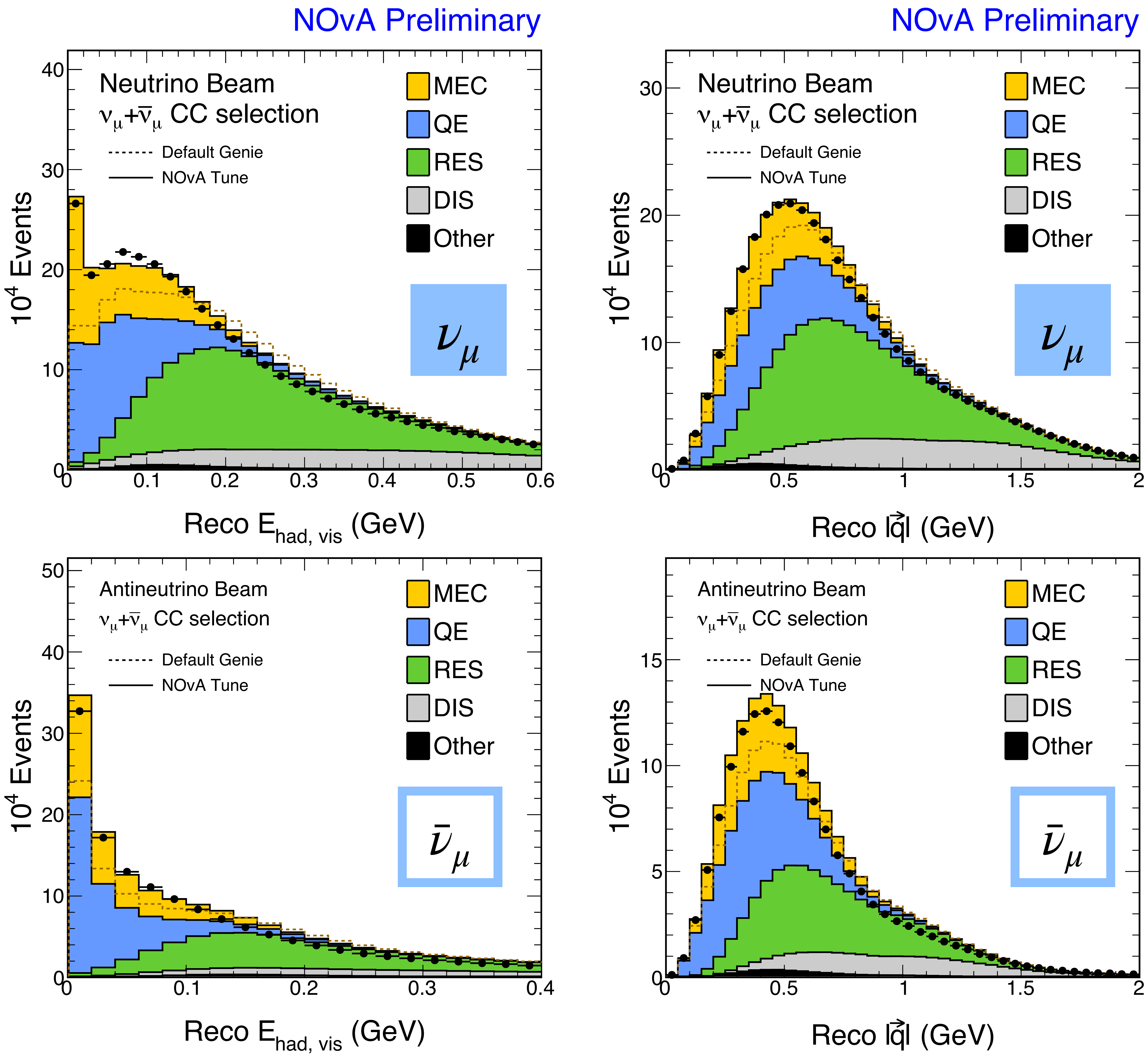


True q_0, |q|



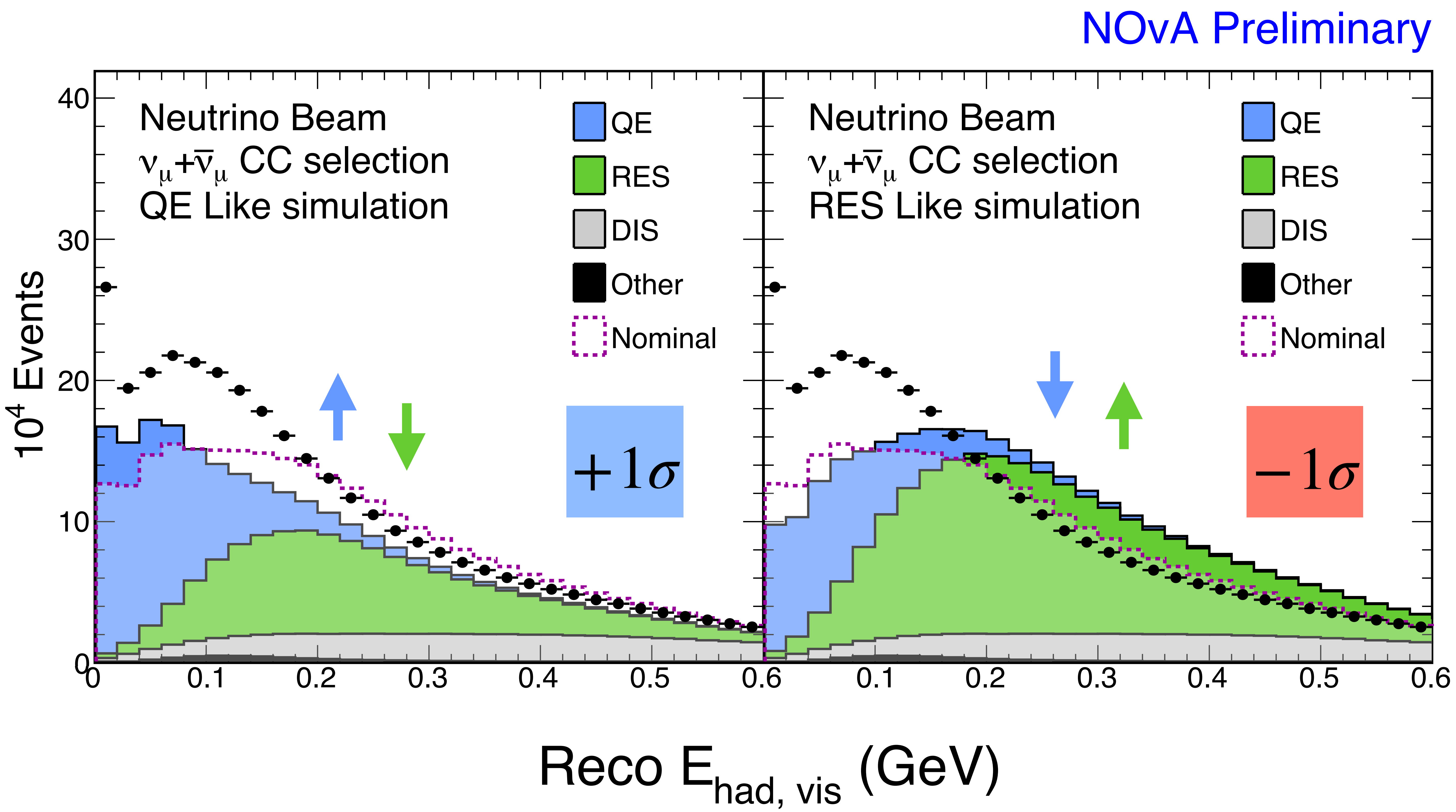
Adjustment of 2p2h interactions

- Projections on the reconstructed q_0 and $|q|$ axes after MEC adjustment.
- Agreement considerably better, but this tuning is unable to correct all of the phase space.



2p2h systematics

- The NOvA 2p2h tune assumes that this is the only piece of the model that is deficient.
- It is absorbing the possibility that other cross section parameters in the model need adjustment.
- The uncertainties take this into account by performing two alternate versions of the 2p2h weights.



QE-enhanced distorted simulation

RES-enhanced distorted simulation

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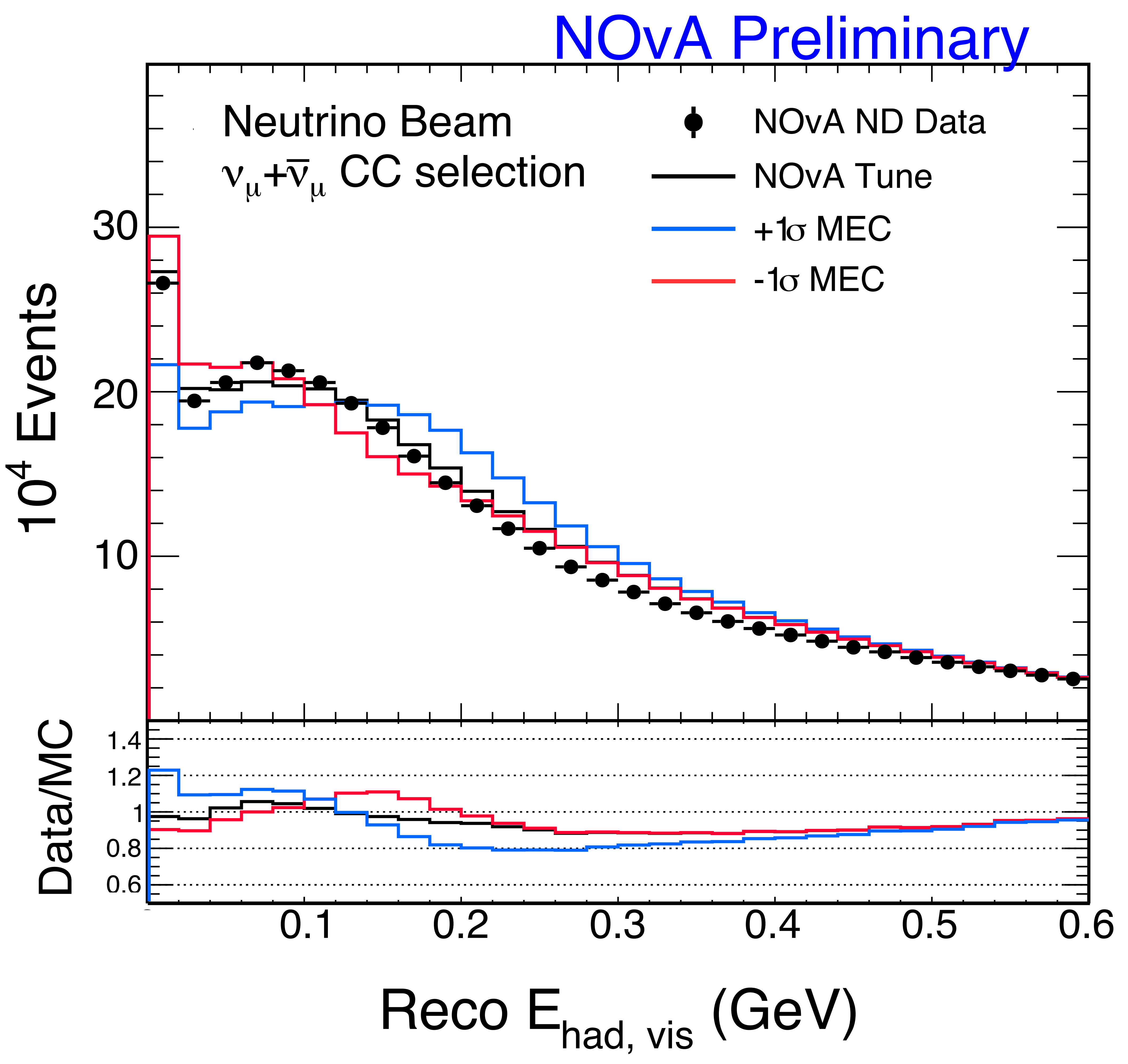
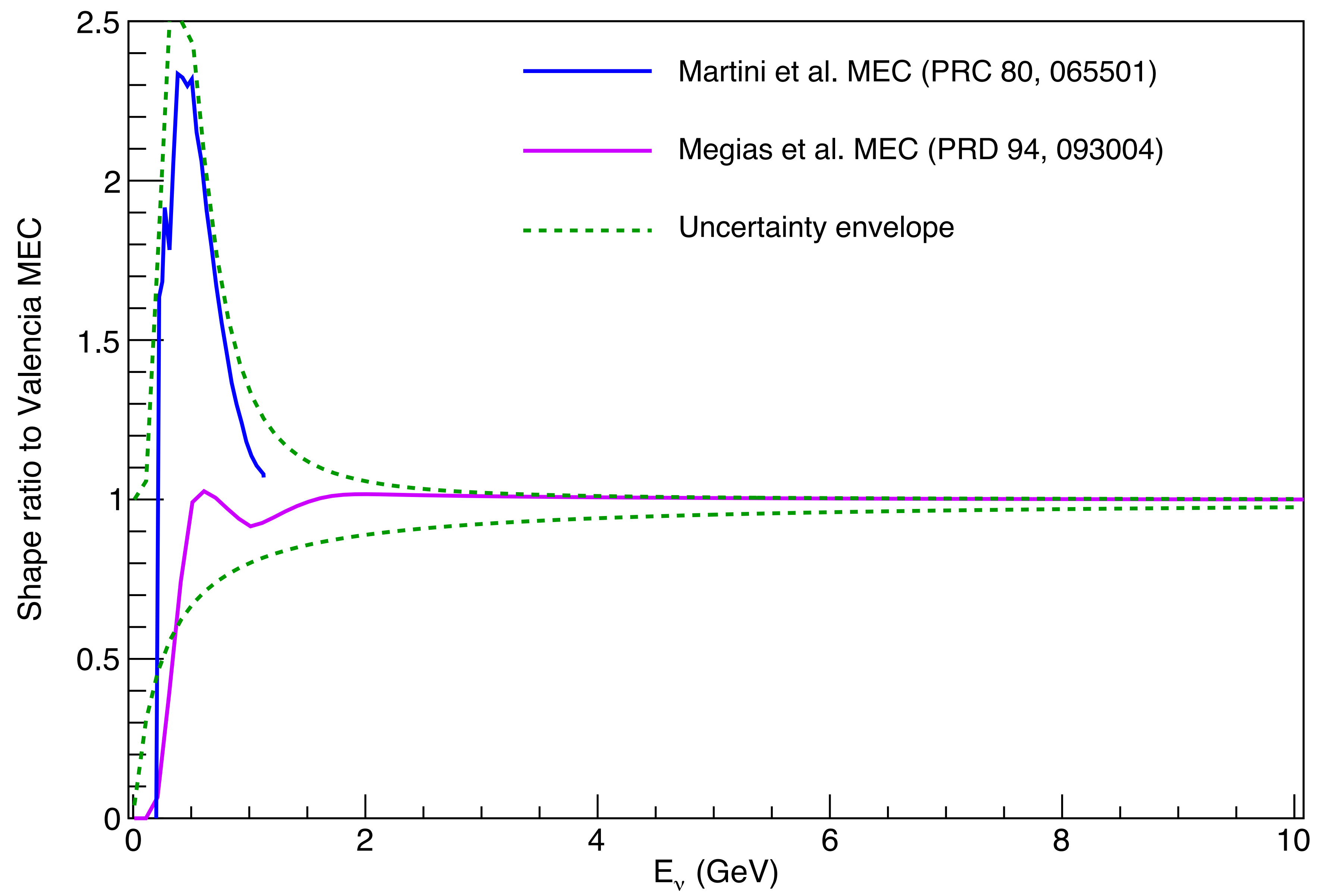
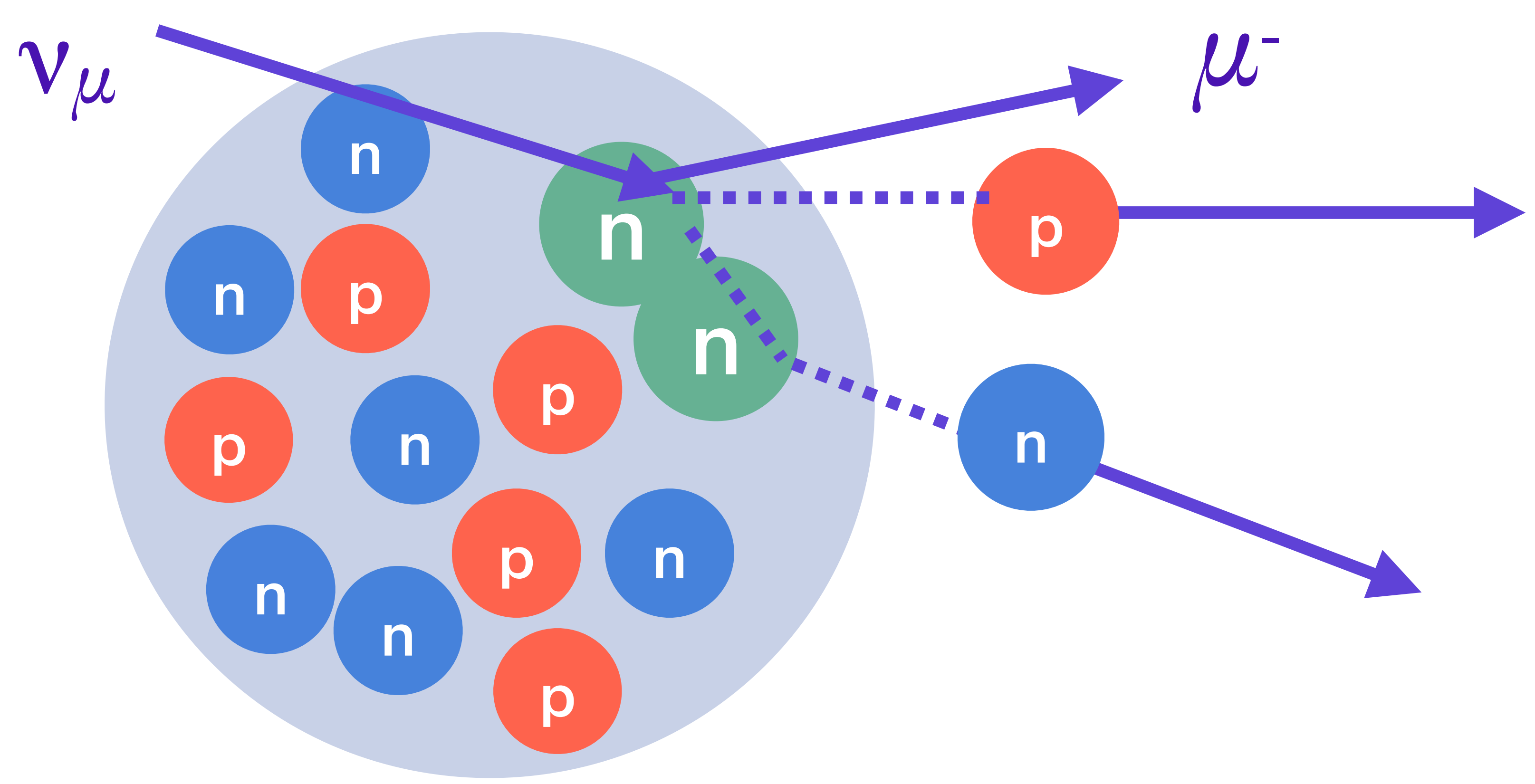


Additional MEC uncertainties

- Theory based uncertainties



- Neutrino energy dependent normalization uncertainty.
- Parametrized as two functions that encapsulate the difference between Valencia MEC and alternate models.



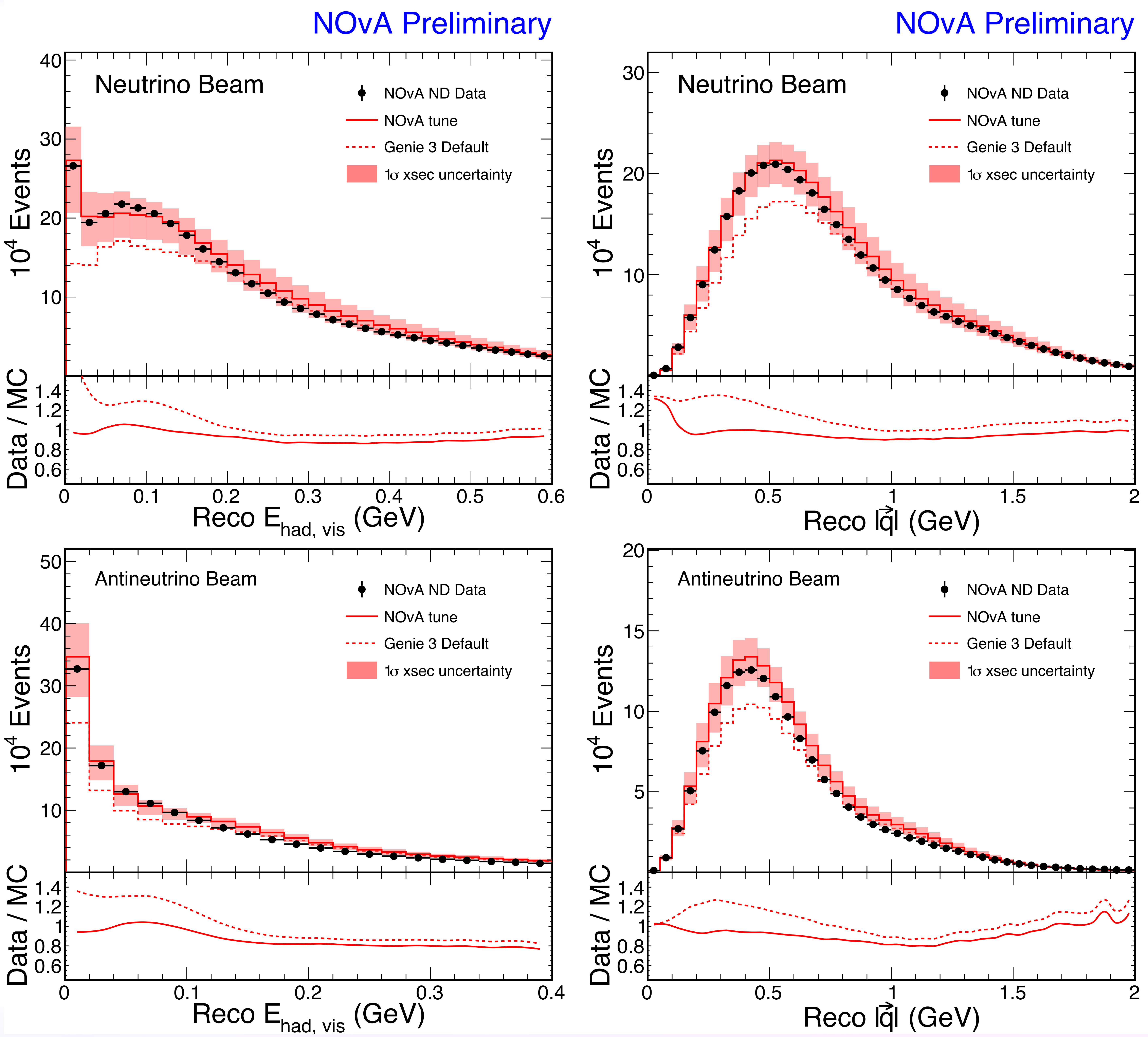
ν $$\frac{np}{np+nn} = 0.69 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases},$$

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

- A function to take into account the ratio of struck nucleons pairs.

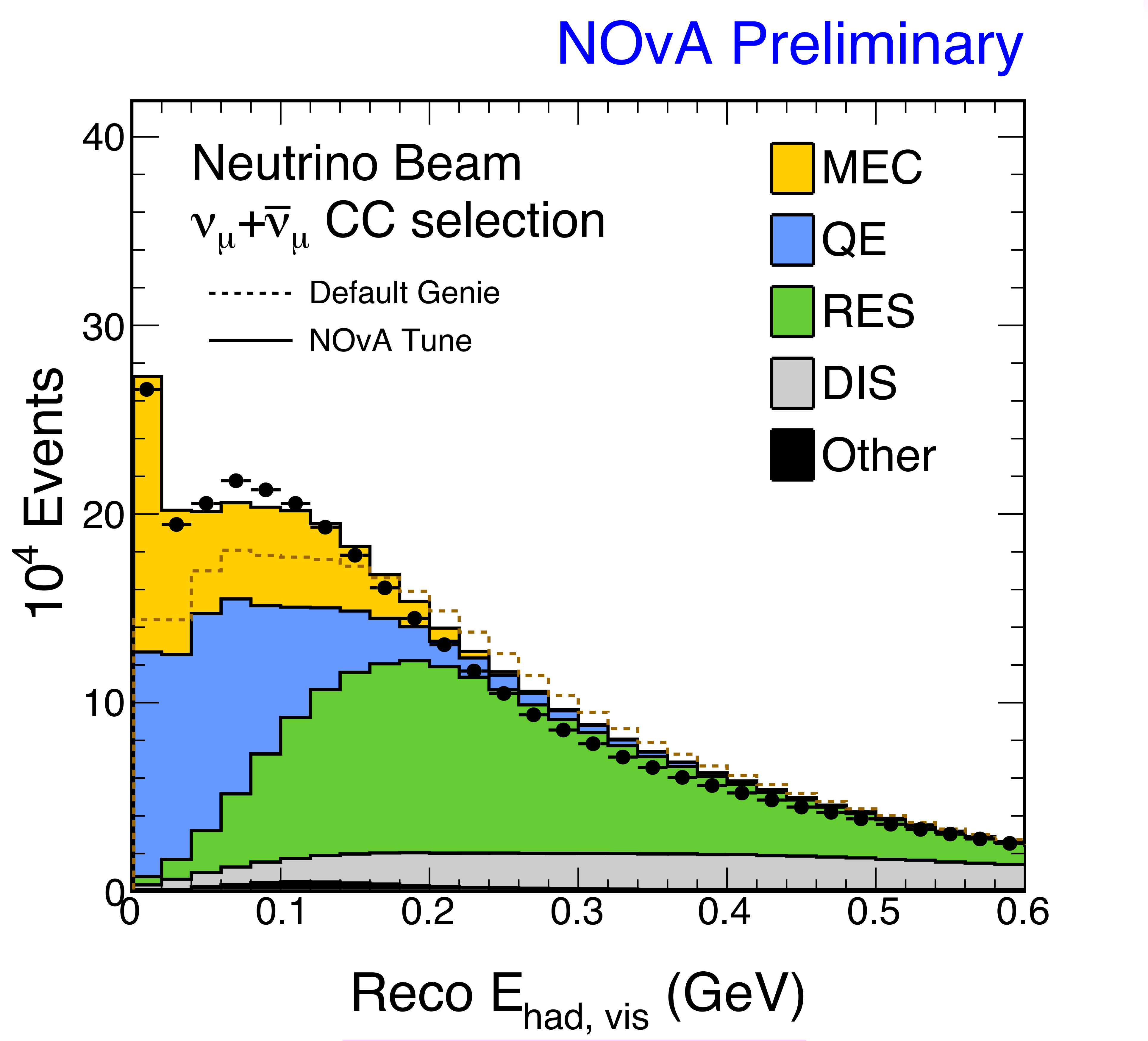
NOvA tune and uncertainties

- Central value agreement is good after FSI and MEC adjustments.
- Cross section uncertainties include custom MEC, FSI in addition GENIE uncertainties.
- These are adequate to take into account remaining differences.



Future plans

- The ND high statistics dataset is rich in information potentially useful to constrain interaction model uncertainties:
  - subdivide into topological categories that separate MEC from other pieces of the model to expose deficiencies,
  - simultaneously fit of MEC and other neutrino interaction parameters using 5 samples to obtain a more robust tuning to our data,
  - fitting framework in progress with both frequentist and Bayesian methods.



Inclusive selection

Topology 1	Topology 2	Topology 3	Topology 4	Topology 5
QE/MEC enhanced 1 track	QE/MEC enhanced 2 tracks	RES enhanced π in final state	RES/DIS enhanced No vis. π	Remaining

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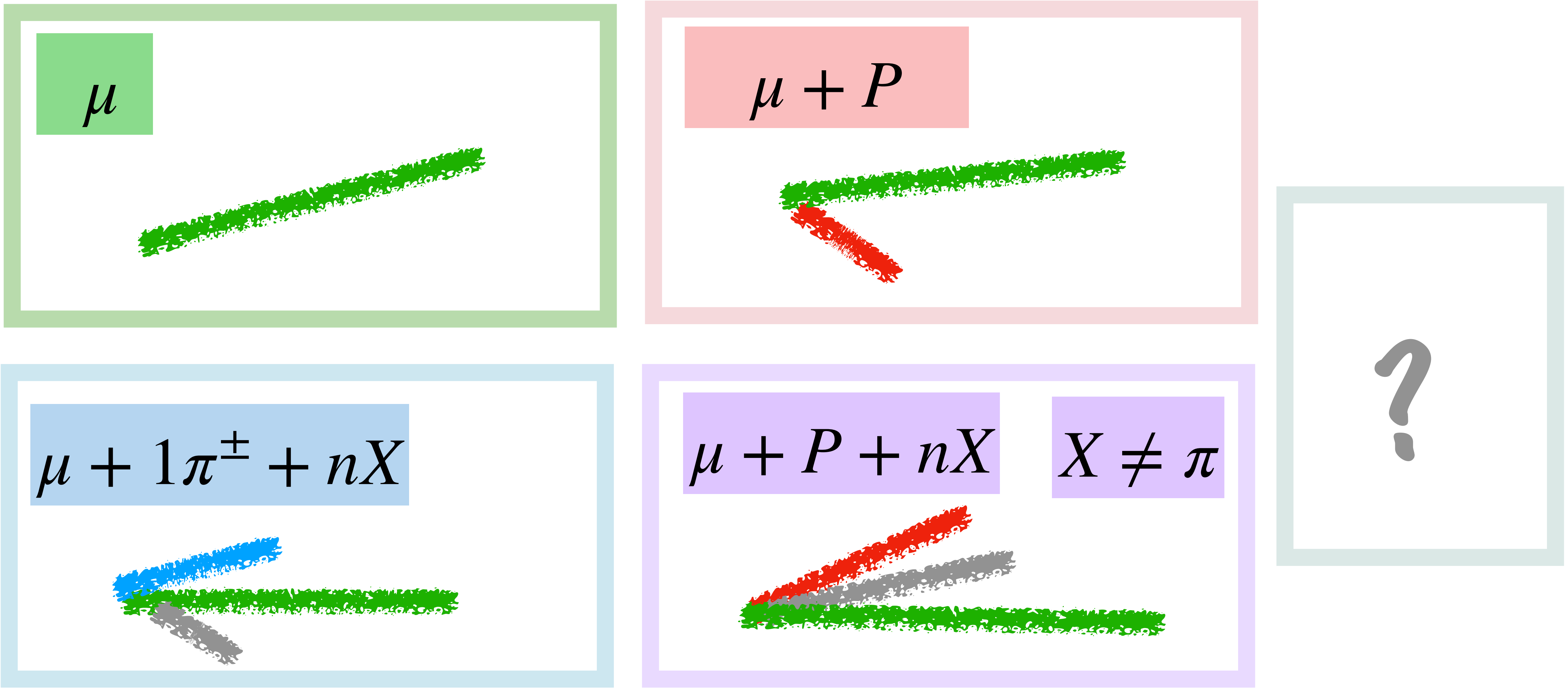
- Samples defined by the number and type of particles identified in the detector:
  - **muons**, **protons**, **charged pions** or **other.**

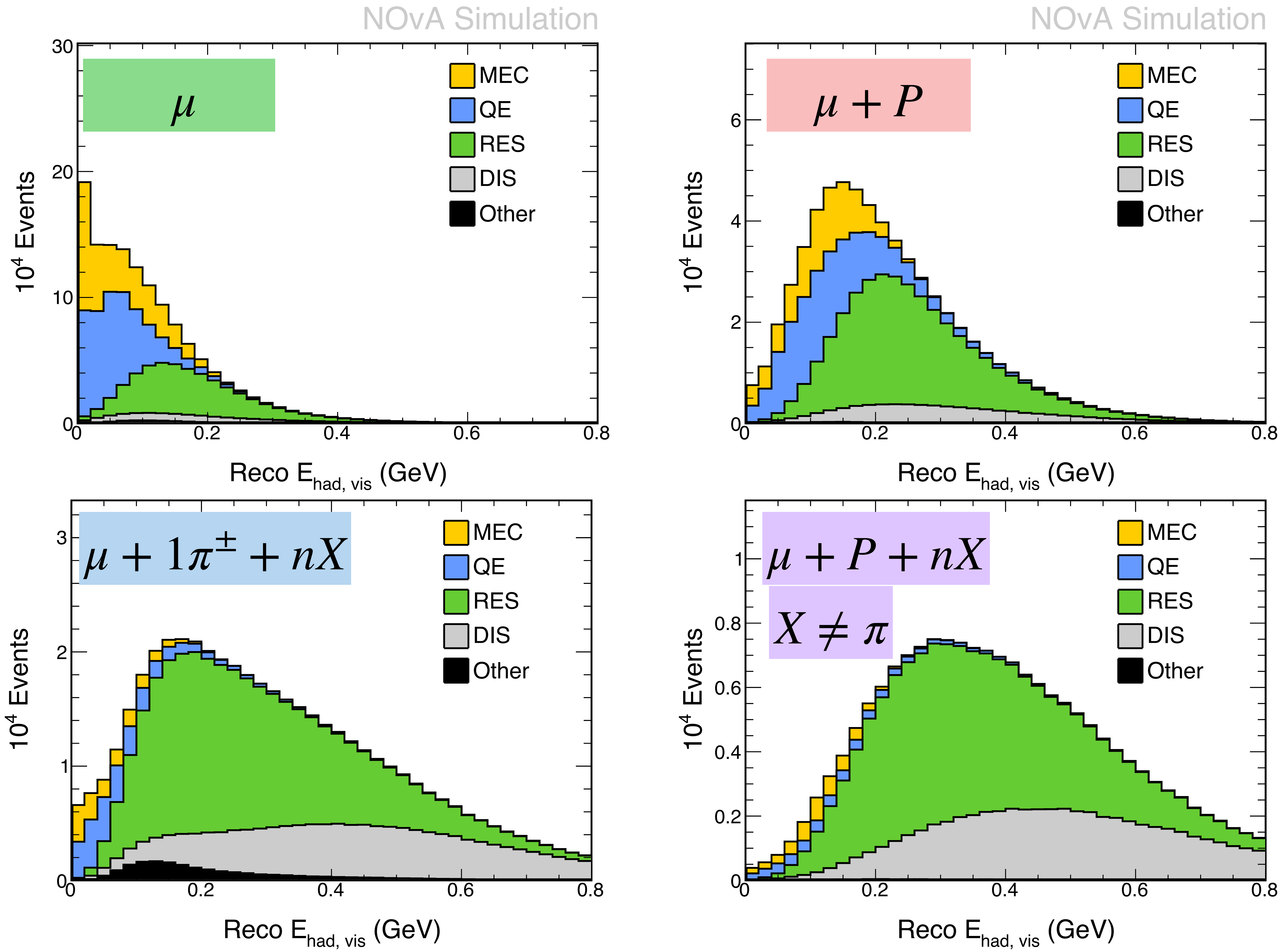


Topology samples for ND fit

- The samples are effective at separating different amounts of true final states and in separating different interaction types

- **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

- NOvA uses GENIE 3.0.6 model with custom adjustments.
- The cross section model needs improvement to describe NOvA data, so we adjust central value:
  - FSI is tuned with external data
  - MEC is tuned using our own ND data
  - Uncertainties are constructed to take into account remaining discrepancies
- ND has a rich dataset useful for improvements in constraining neutrino interaction modeling. New work in progress toward including all cross section systematic uncertainties while adjusting MEC.

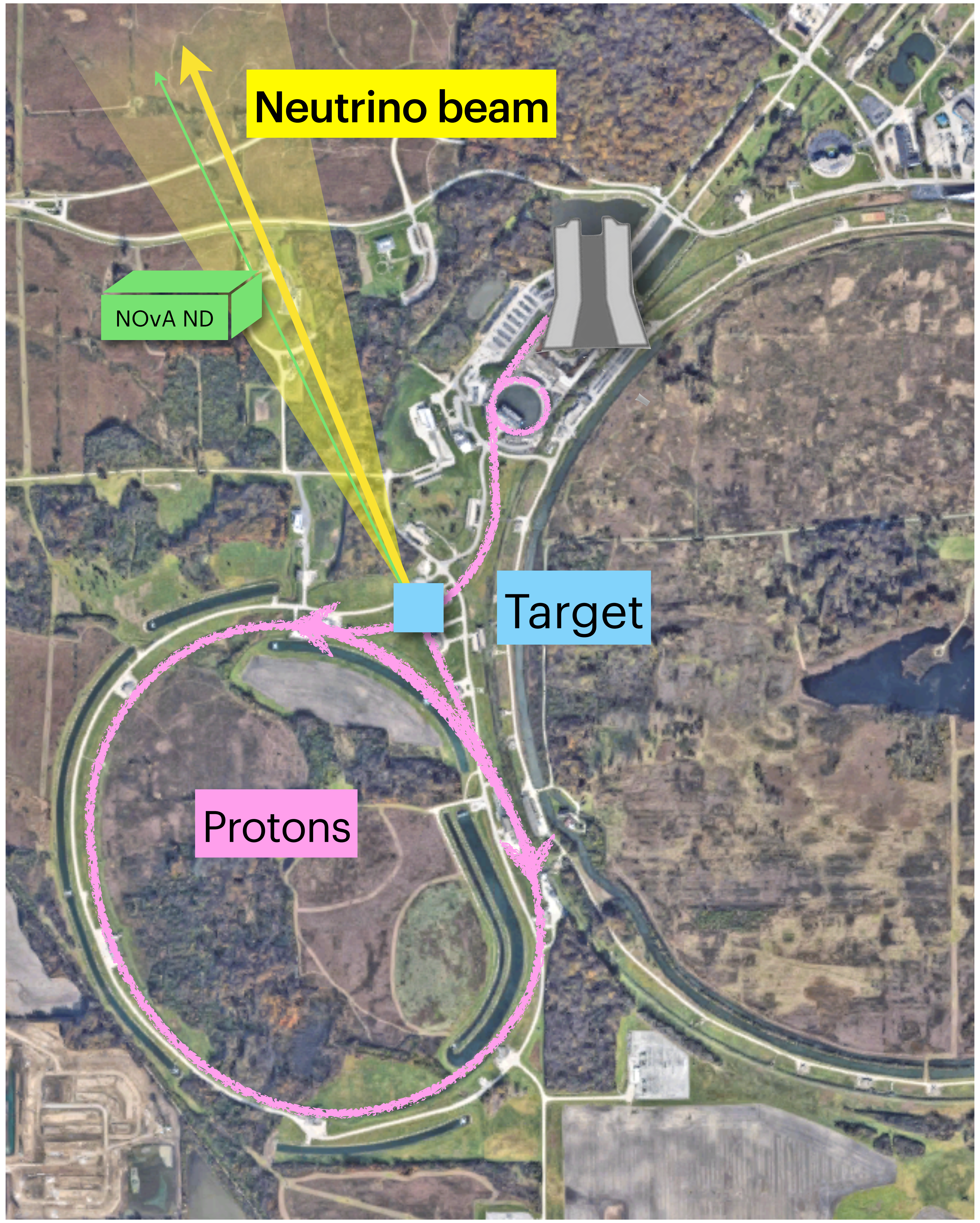
Duluth, MN
June 2022

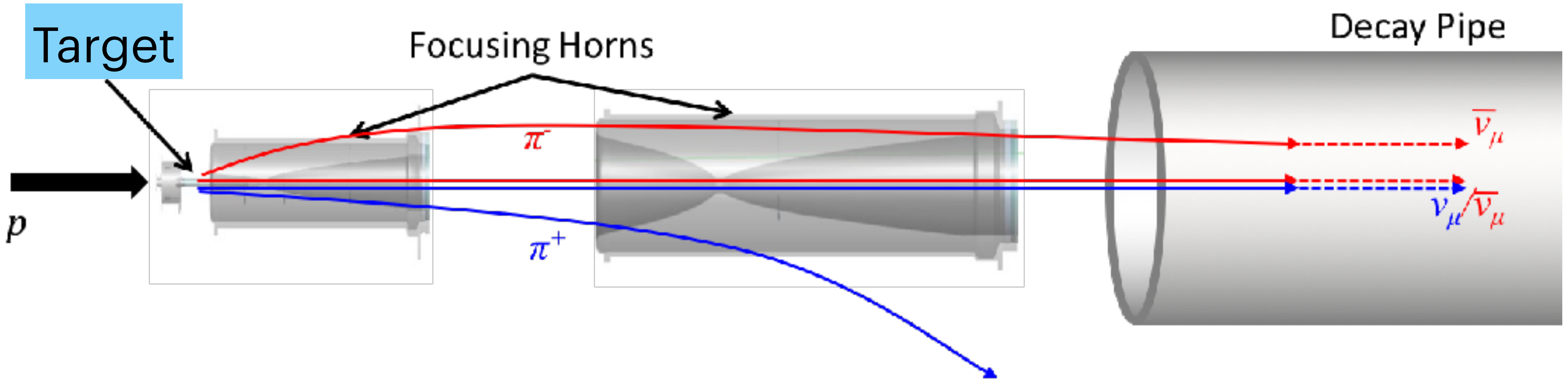
NOvA

Thanks for your attention!

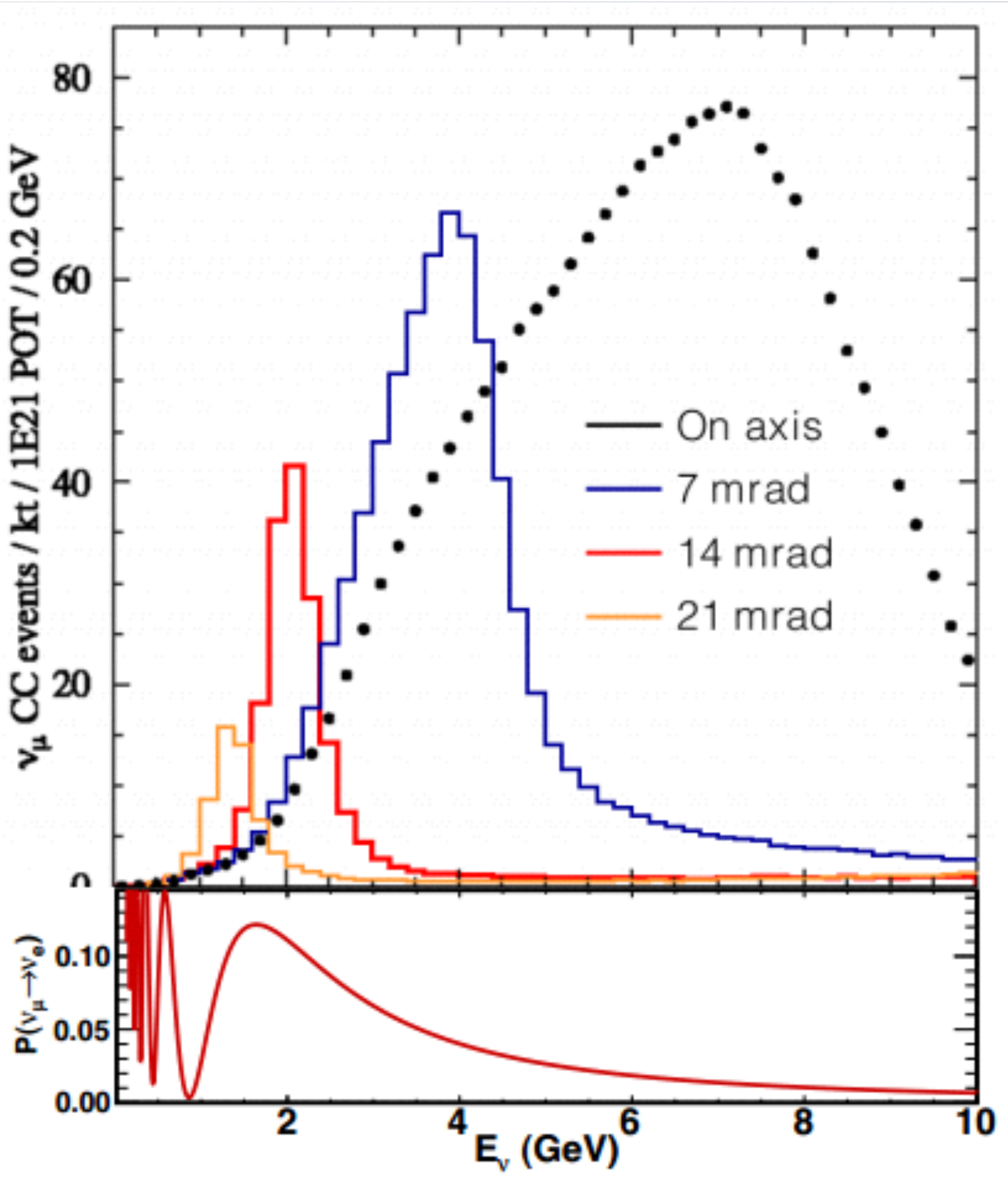
Backup

The NuMI Beam

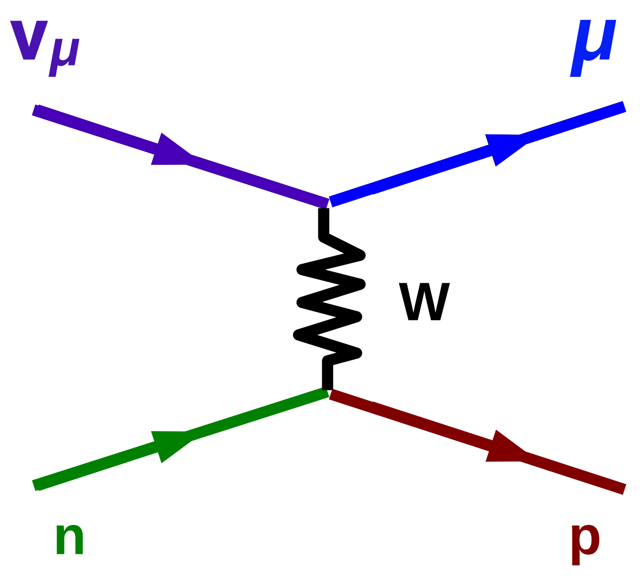




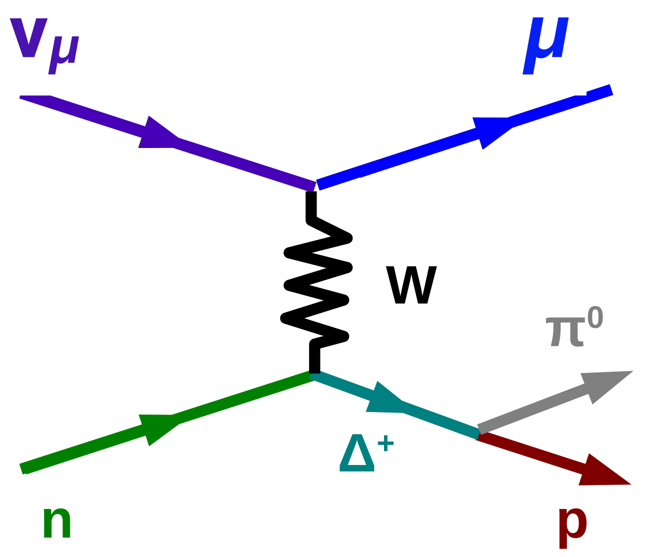
- 120 GeV protons from the Main Injector hit a graphite target producing a shower of mesons.
- +(-)Charged pions and kaons are focused by a magnetized horns and decay into (anti)neutrinos.
- The NOvA detectors are off-axis by 14.6 mrad, which produces a spectrum with a peak at ~2GeV, near the oscillation maximum.



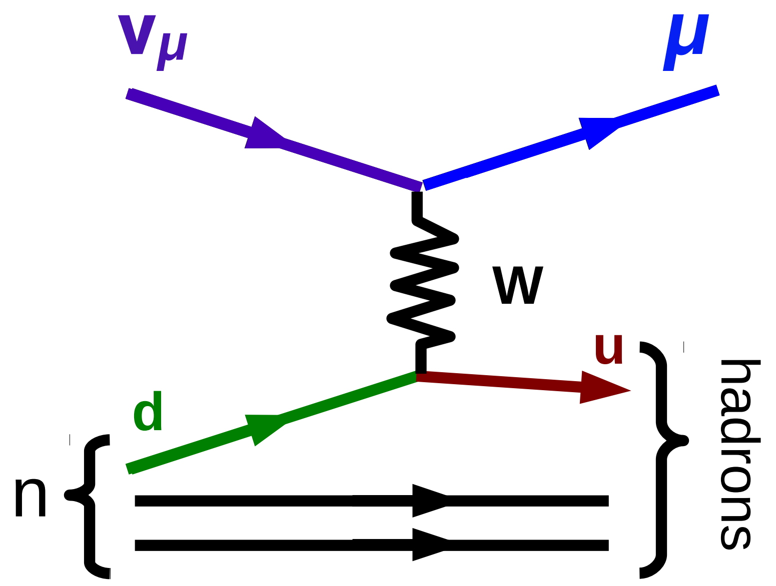
ν_μ interactions in NOvA



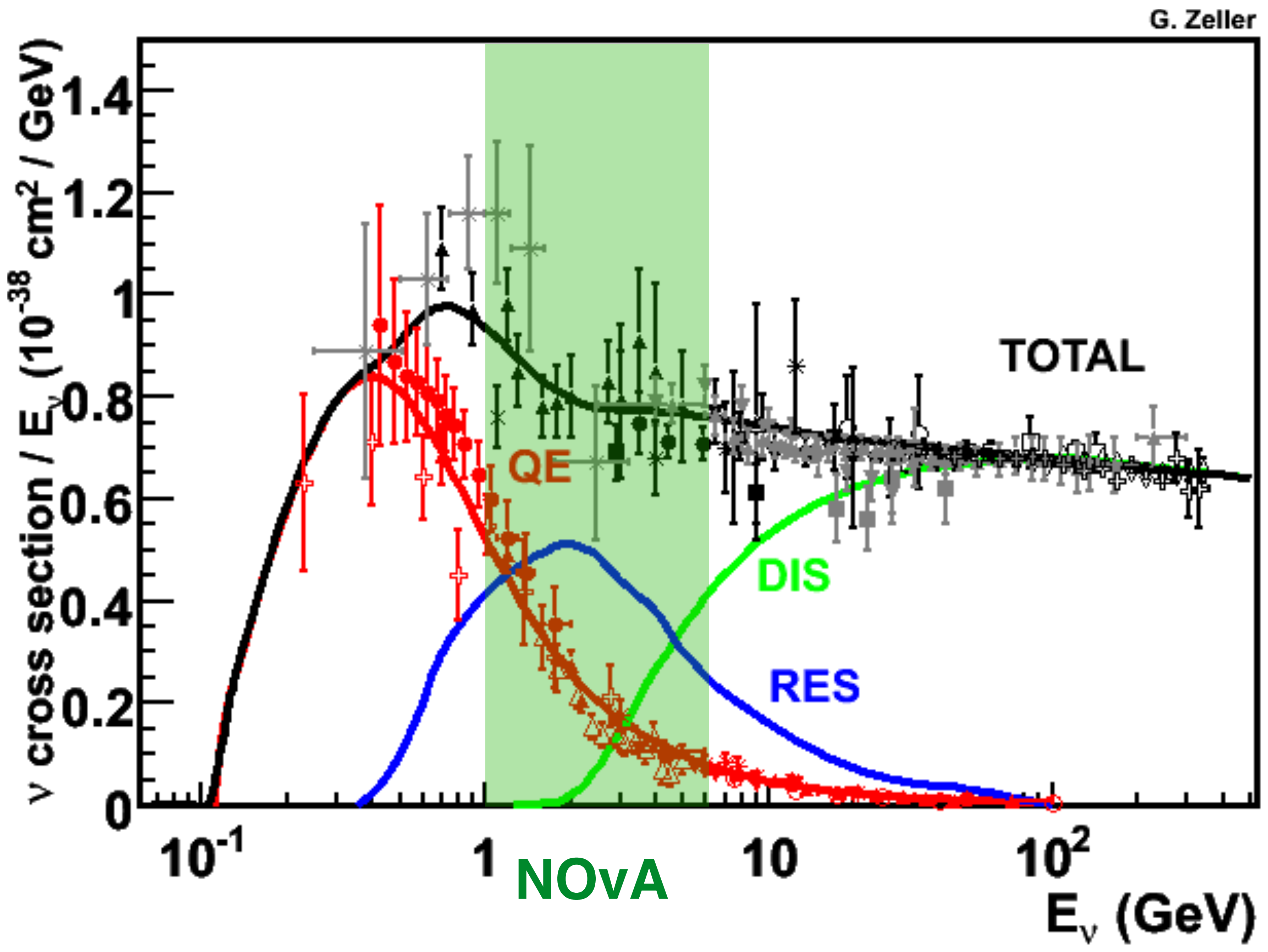
Quasi-elastic (QE)



Resonance (RES)



Deep Inelastic Scattering (DIS)

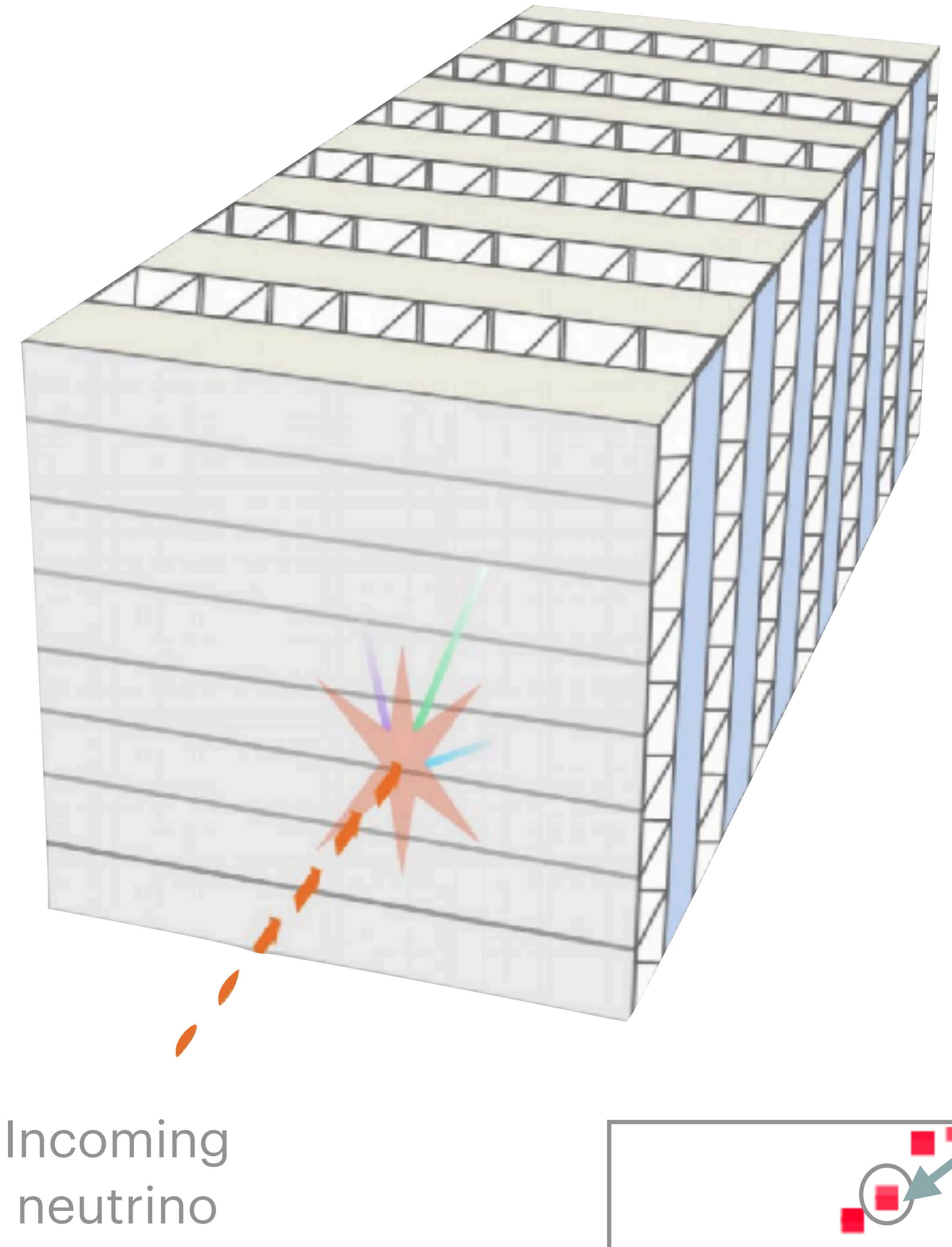


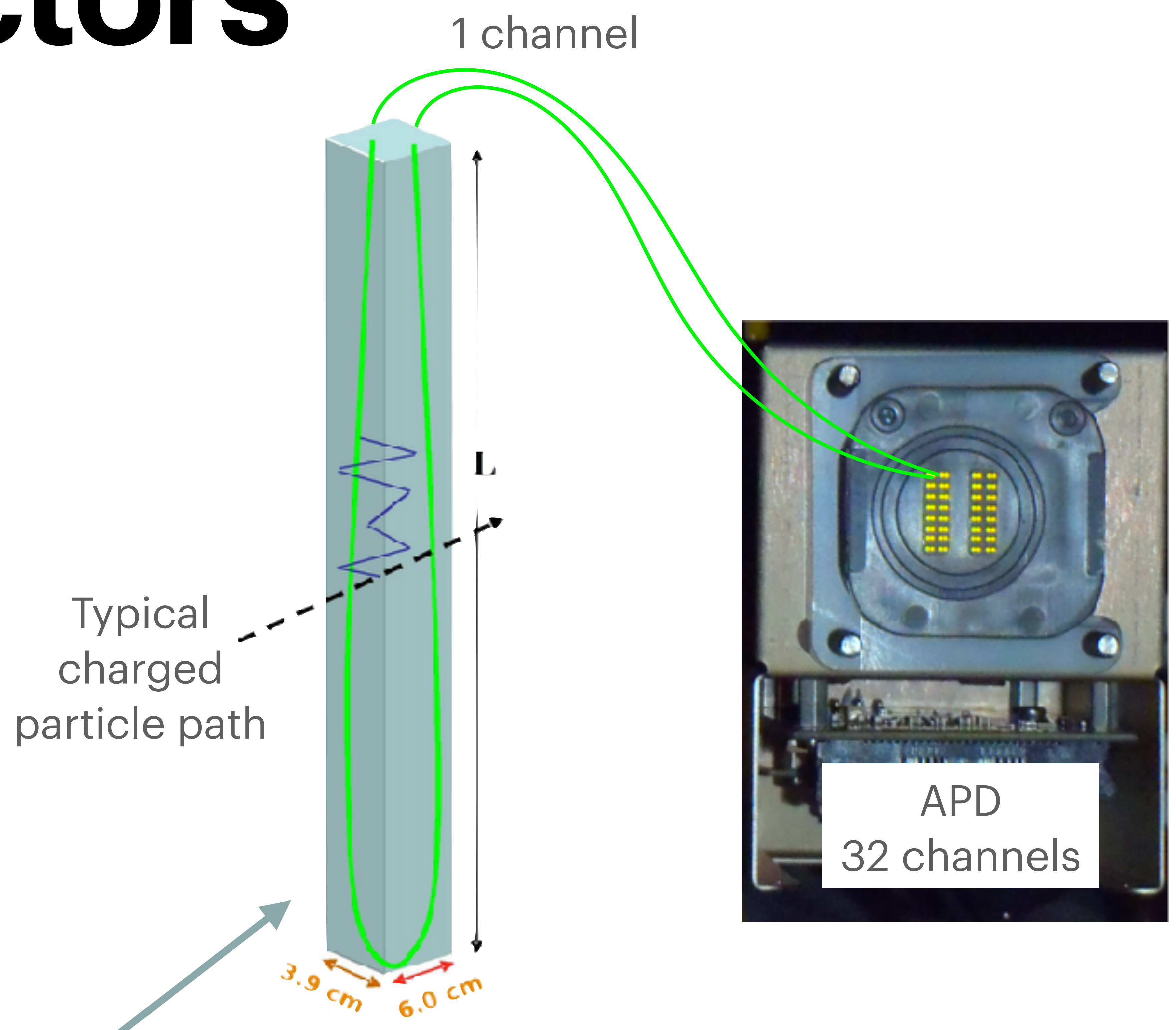
J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

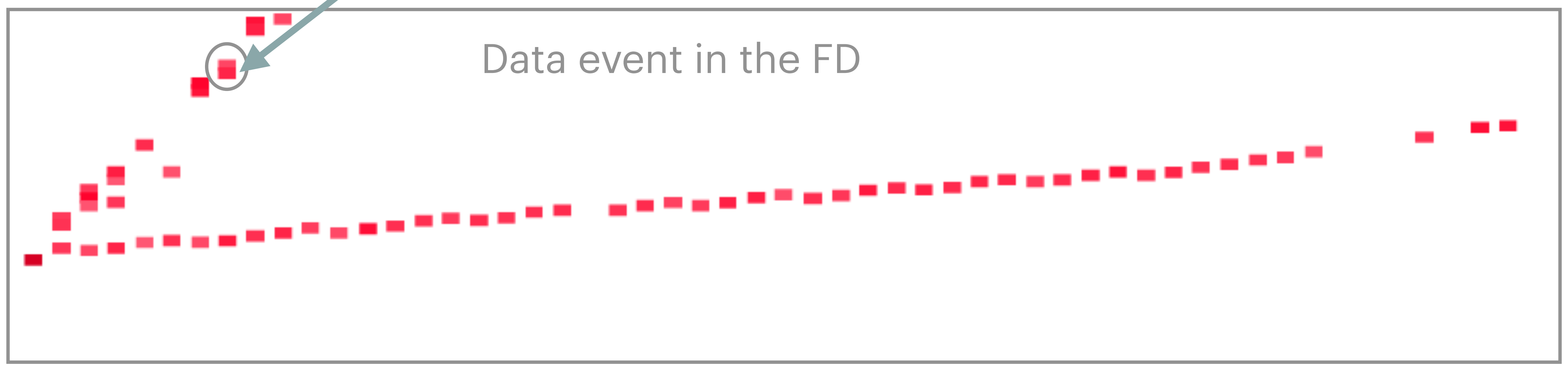
- NOvA's spectrum peaks at ~2GeV

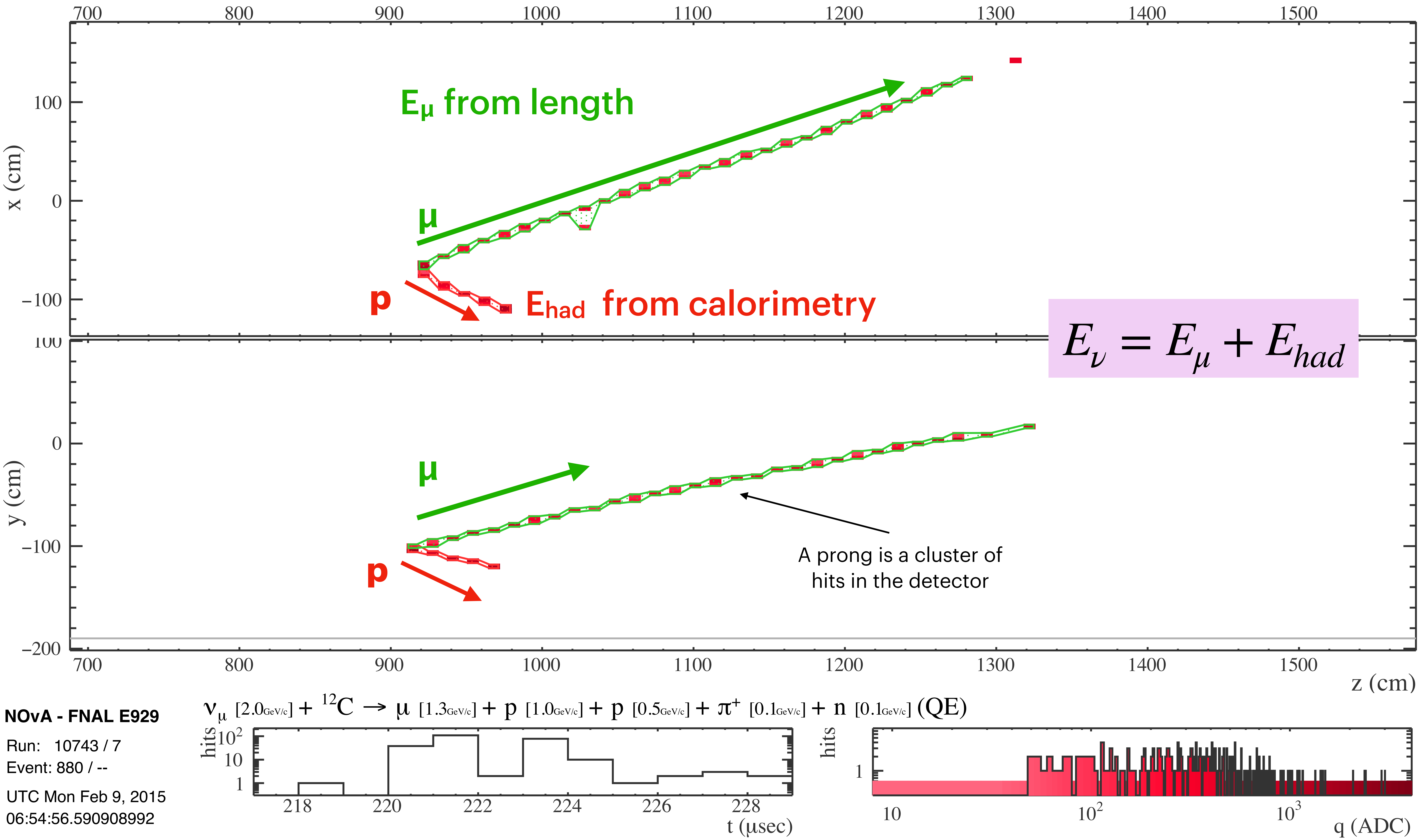
The NOvA detectors

- Extruded PVC cells filled with liquid scintillator arranged in alternating planes.
- Light is produced when charged particles pass through the cells.
- The light is collected by a wavelength shifting fiber and transported to an Avalanche Photo Diode (APD), which amplifies the signal.

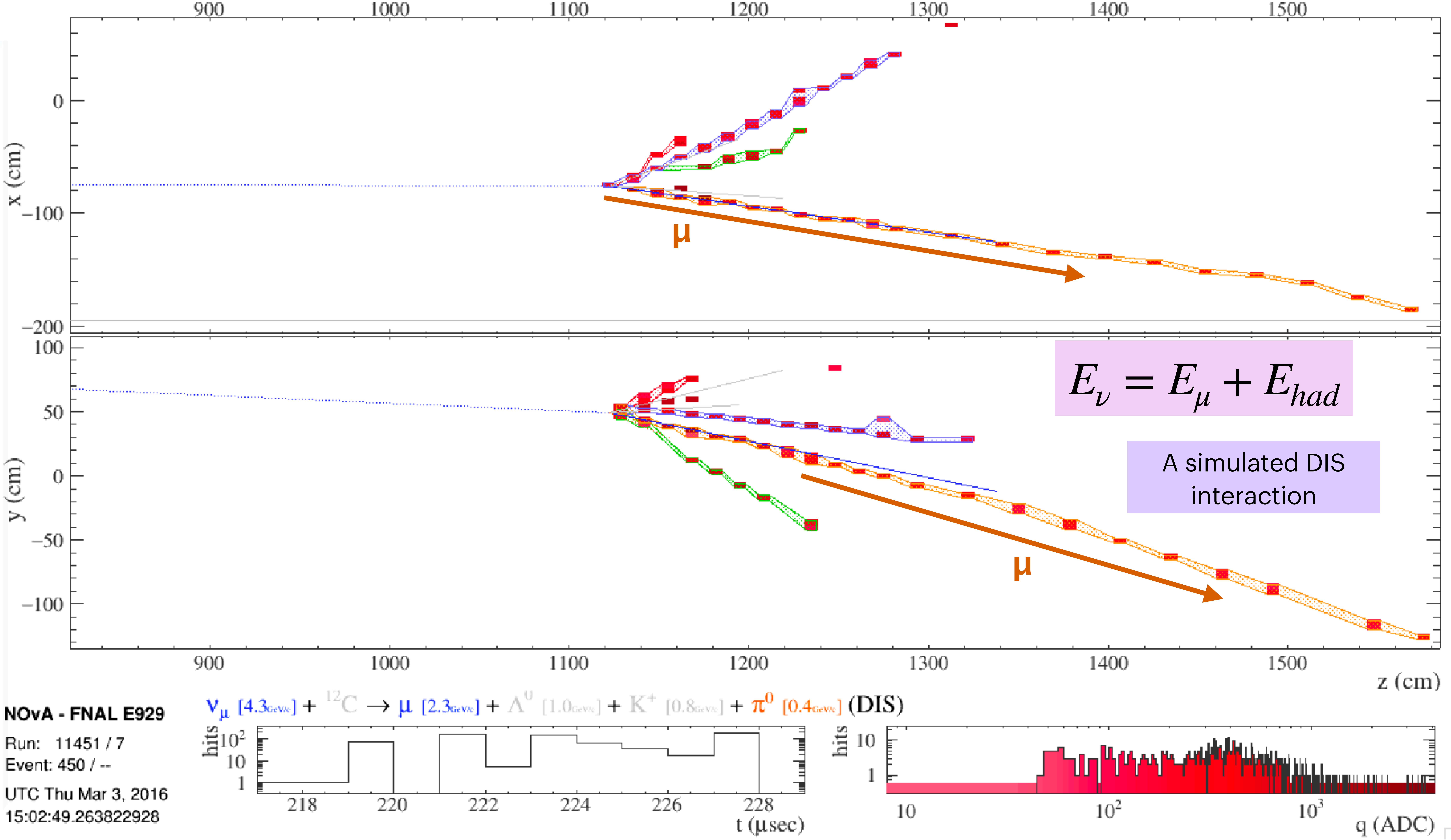






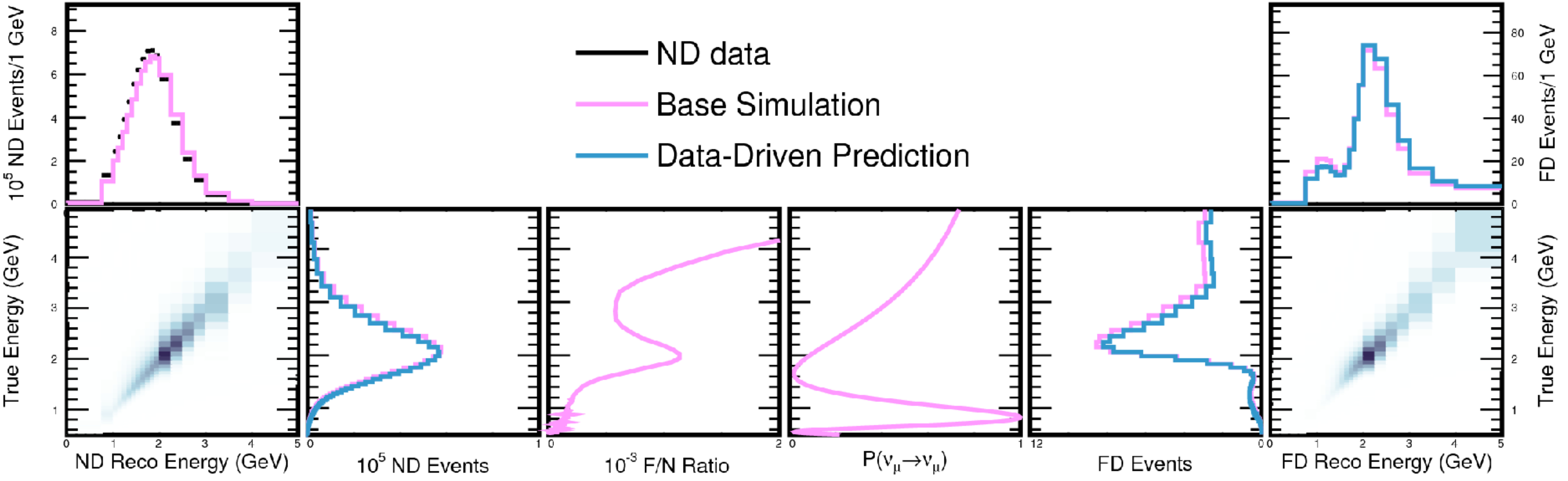


Eμ from length
μ
p
Ehad from calorimetry
$E_\nu = E_\mu + E_{had}$
μ
p
A prong is a cluster of hits in the detector
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 10743 / 7
Event: 880 / --
UTC Mon Feb 9, 2015
06:54:56.590908992
νμ [2.0GeV/c] + 12C → μ [1.3GeV/c] + p [1.0GeV/c] + p [0.5GeV/c] + π+ [0.1GeV/c] + n [0.1GeV/c] (QE)
hits
t (μsec)
q (ADC)

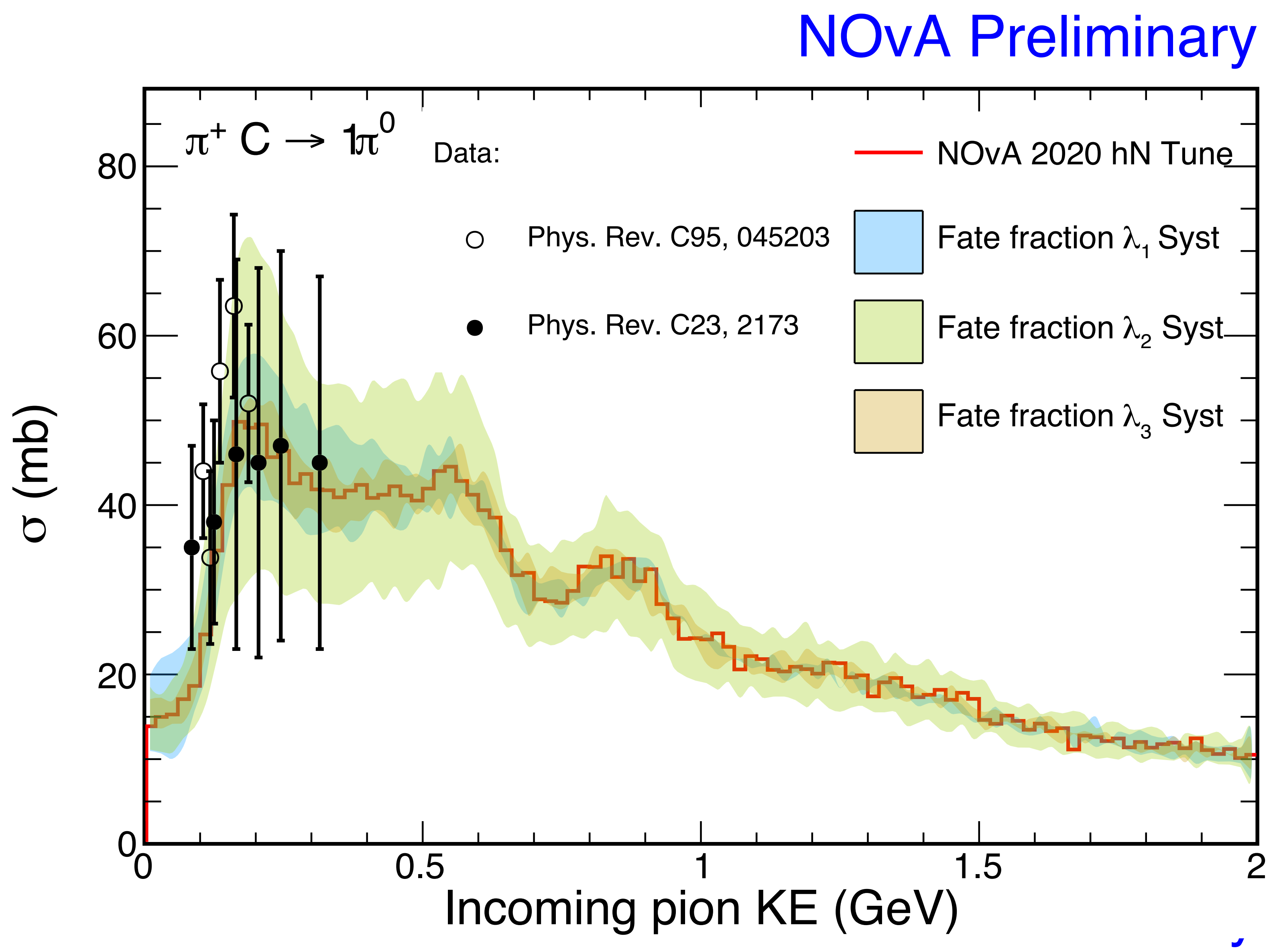

$E_\nu = E_\mu + E_{had}$
A simulated DIS interaction
μ
μ
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11451 / 7
Event: 450 / --
UTC Thu Mar 3, 2016
15:02:49.263822928
ν_μ [4.3GeV/c] + ^{12}C → μ [2.3GeV/c] + Λ^0 [1.0GeV/c] + K^+ [0.8GeV/c] + π^0 [0.4GeV/c] (DIS)
hits
t (μsec)
q (ADC)

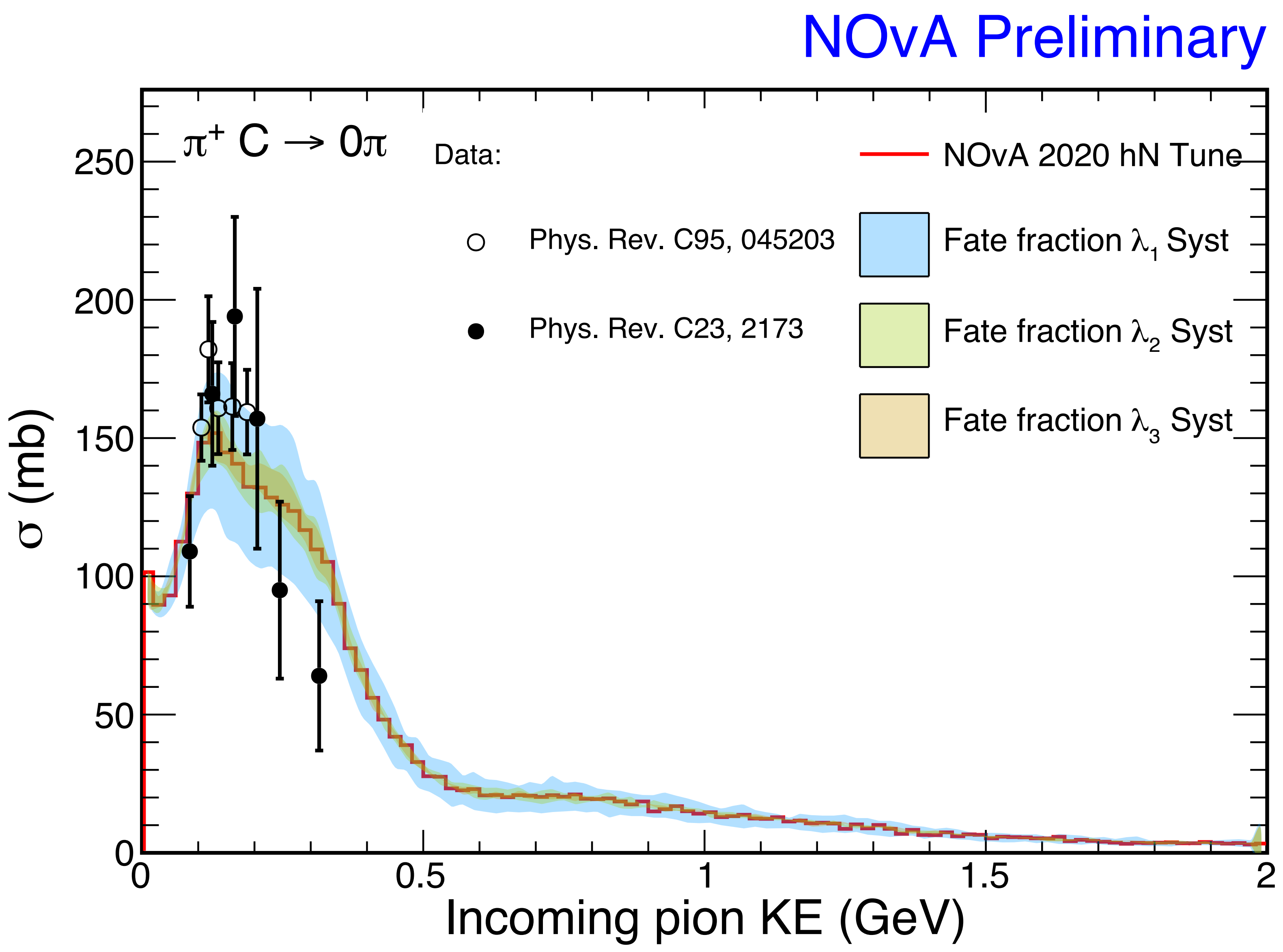
Near to Far extrapolation

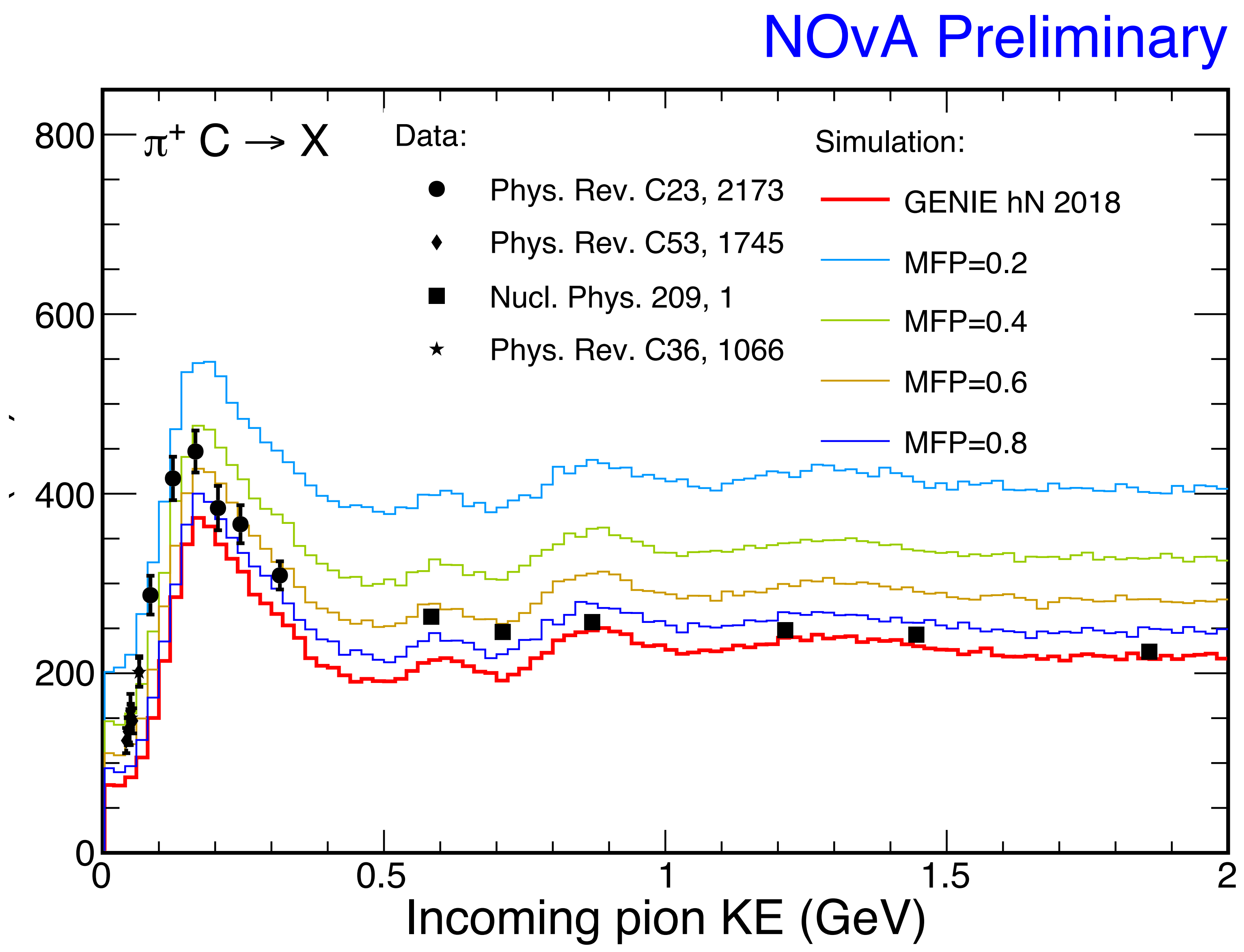
Concept: Identical detectors share all the ingredients except the oscilliations → Correct the true *event rate* (Φ×σ×...) using the ND and propagate that (F/N captures geometrical differences between detectors)

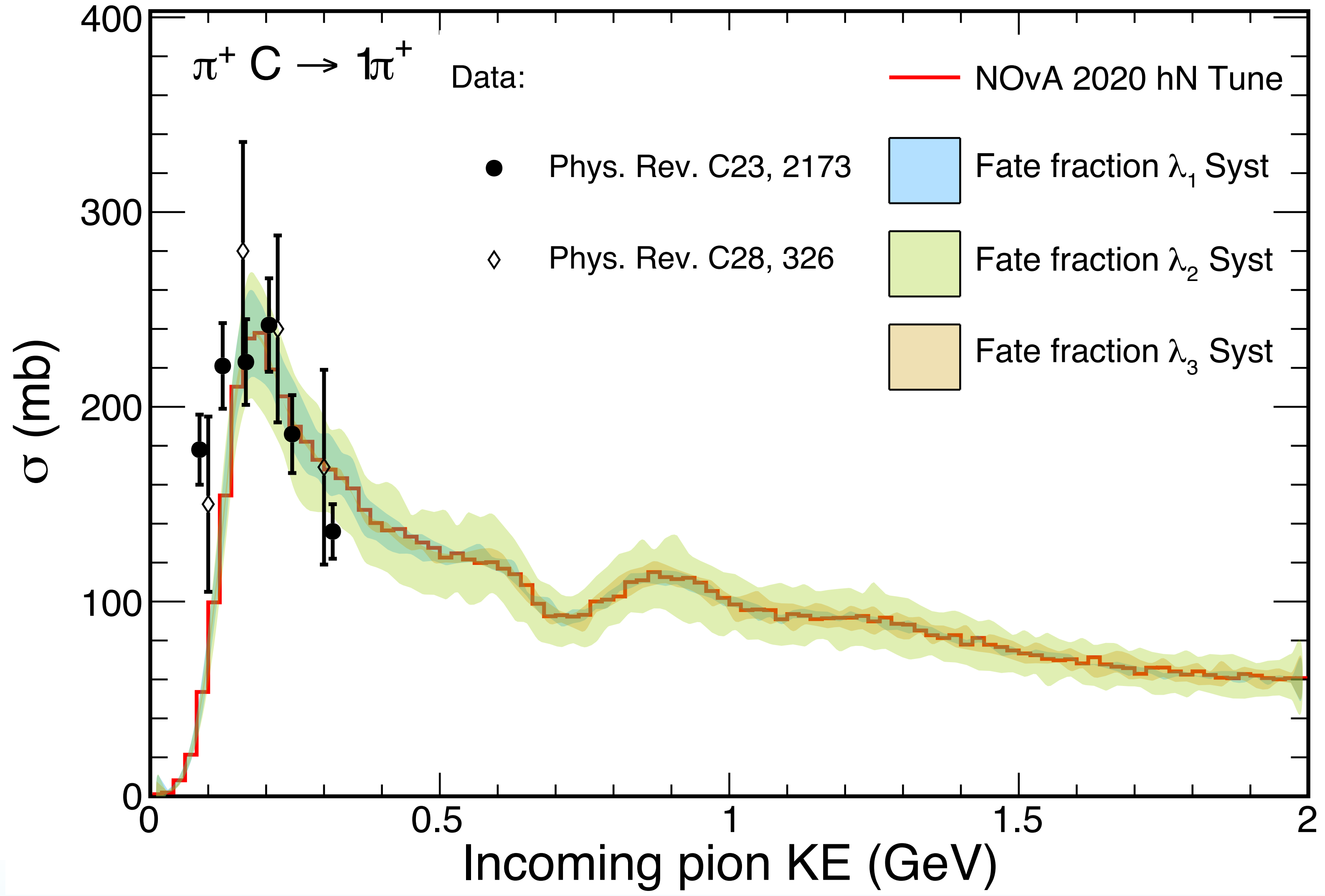


FSI fate fraction and MFP uncertainties







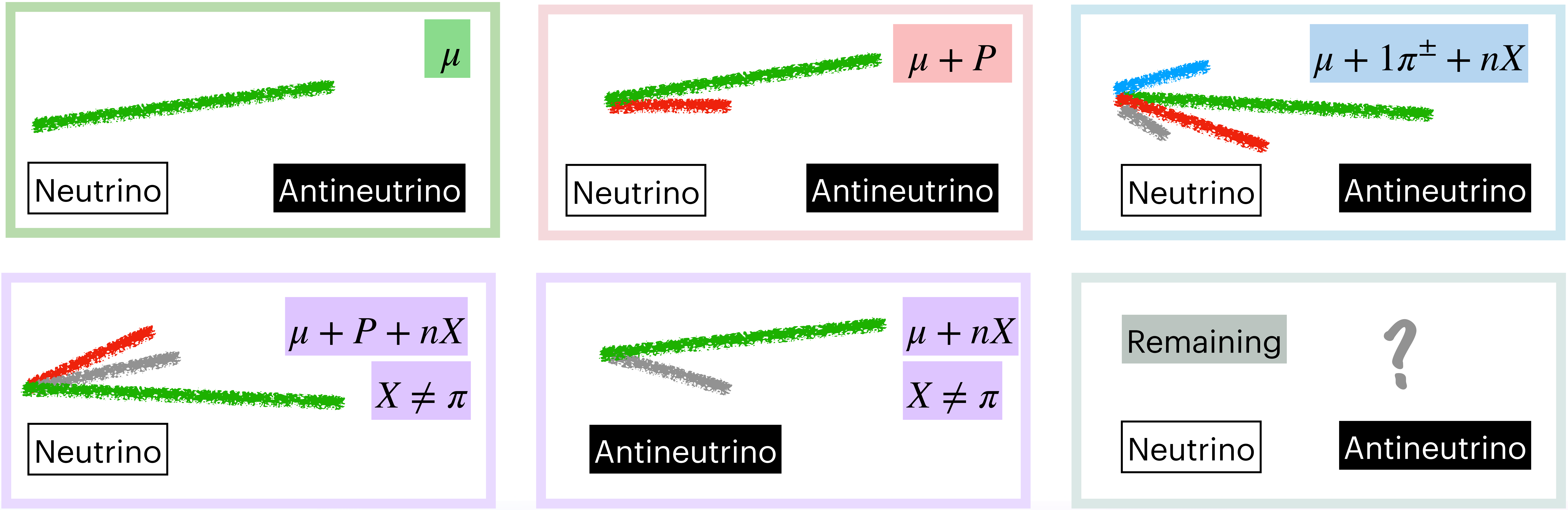


- Three uncorrelated uncertainties of the “fate fractions”.
- For fABS, fCX and fQE, we construct a covariance matrix, and the resulting eigenvalues and eigenvectors provide uncorrelated error variations for each parameter.

- MFP uncertainty brackets external data between the values 0.4 and 0.8.

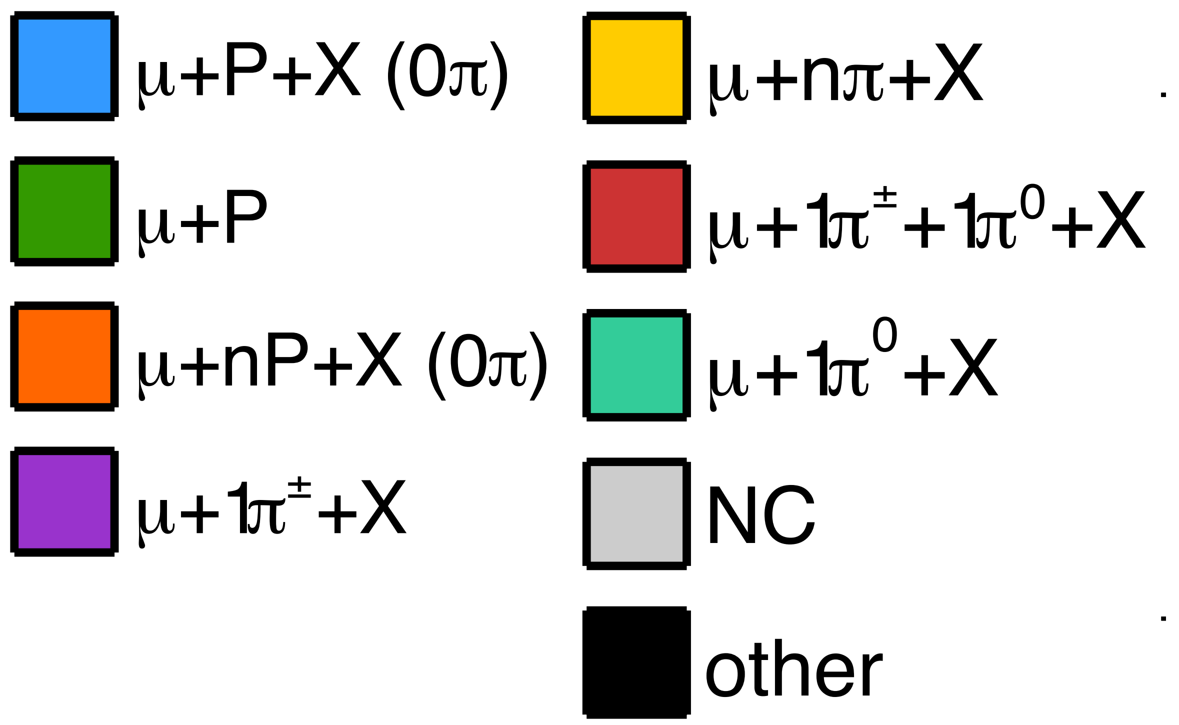
Subdividing the ND dataset

- We have developed 10 non-overlapping samples (5 for neutrino and 5 for antineutrino), defined by the number and type of prongs visible in the detector.
- The prongs are classified according to a convolutional neutral network as **muons**, **protons**, **charged pions** or **other.**

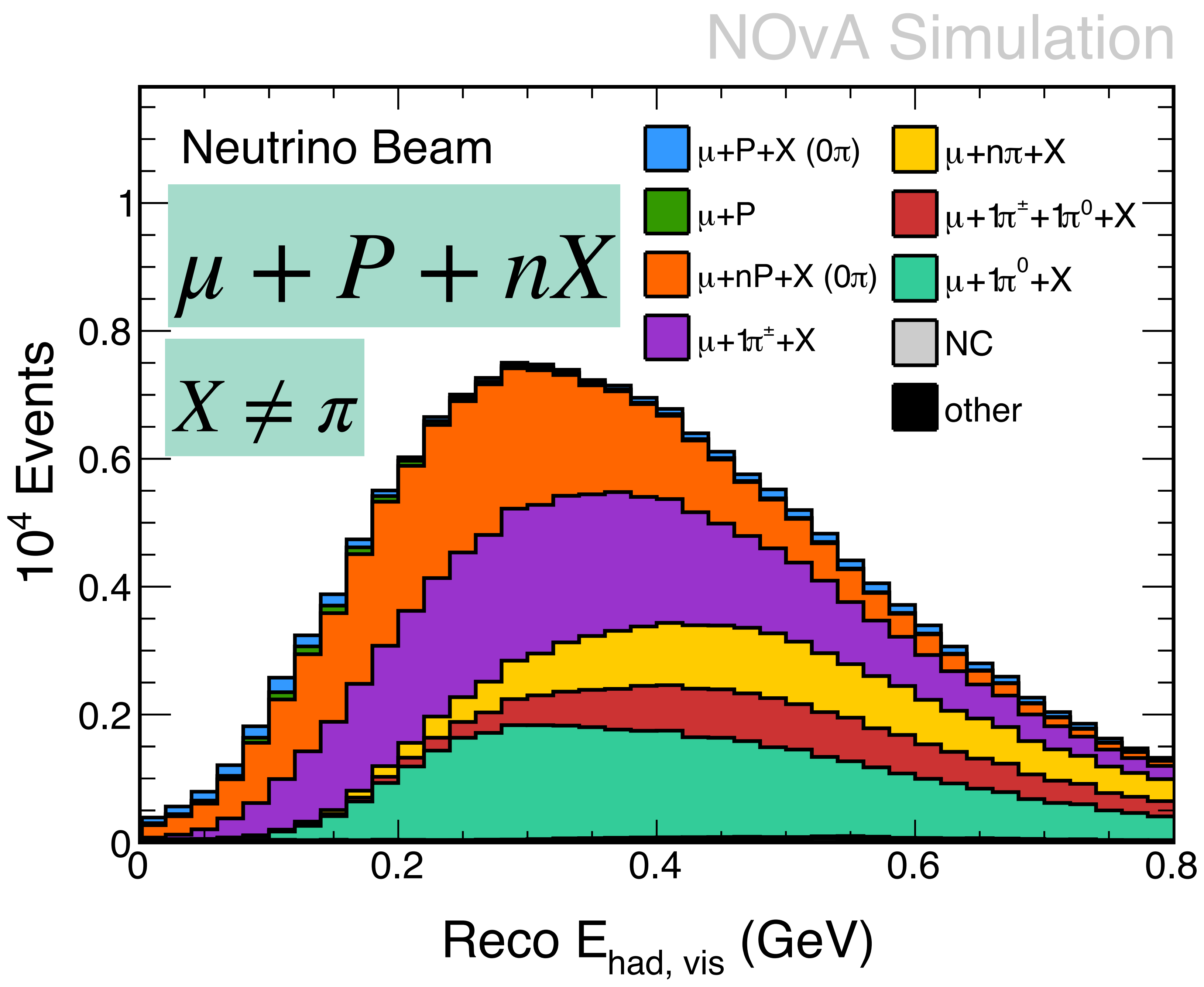


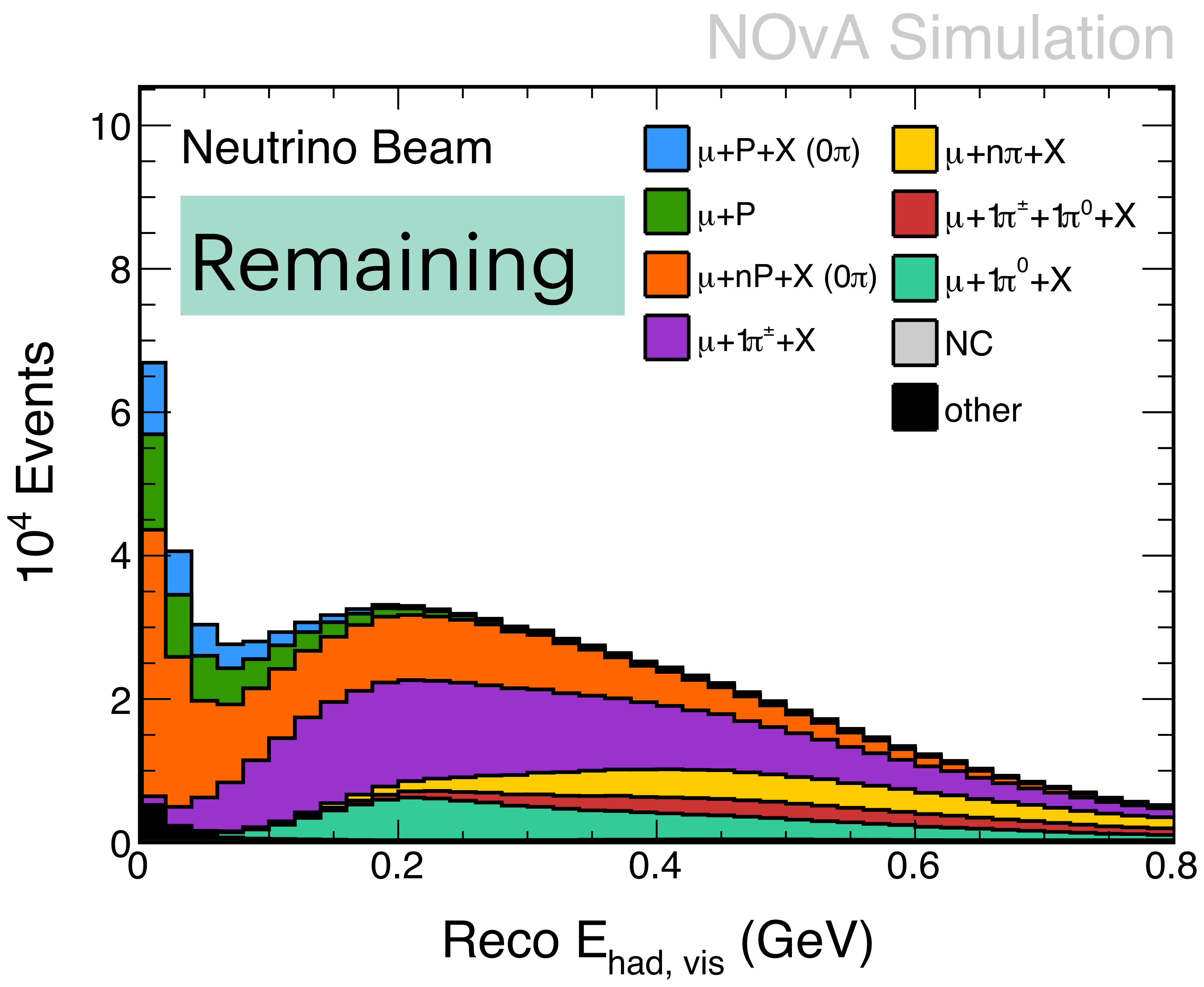
True final states in ND simulation

- The samples are effective at separating different amounts of final states.
- **μ** and **μ+P** samples contain mostly interactions without pions.
  - Also dominated by Quasi-Elastic and Meson Exchange Current interactions.
- **μ+π+X** sample has a high purity of interactions with one charged pion.



True final states in ND simulation





- **μ+P+X** contains a large fraction of interactions with multiple pions.
- The remaining sample contains a mixture of all the categories.
- These are also dominated by Resonance and Deep-Inelastic Scattering interactions.