Cross section model tuning and multiplicity studies in NOvA

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For the NOvA collaboration

New Perspectives
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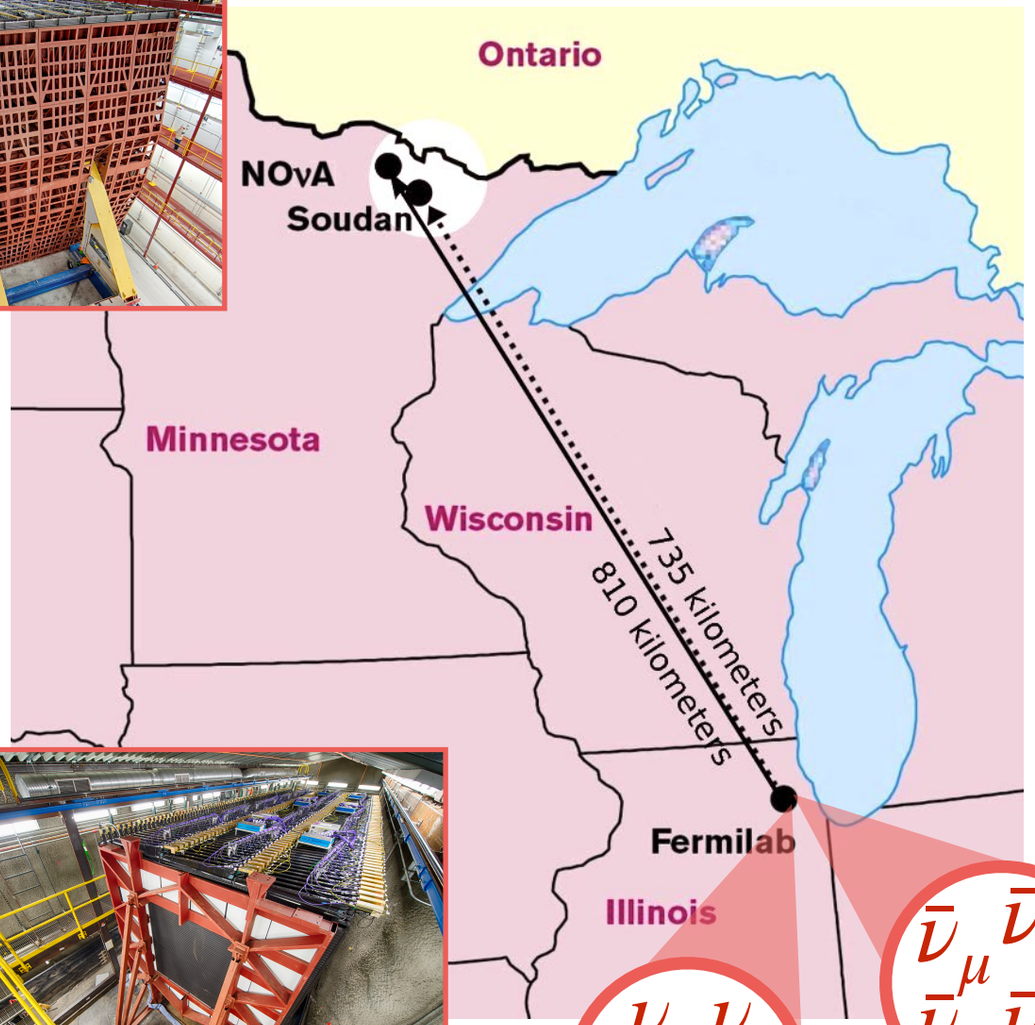
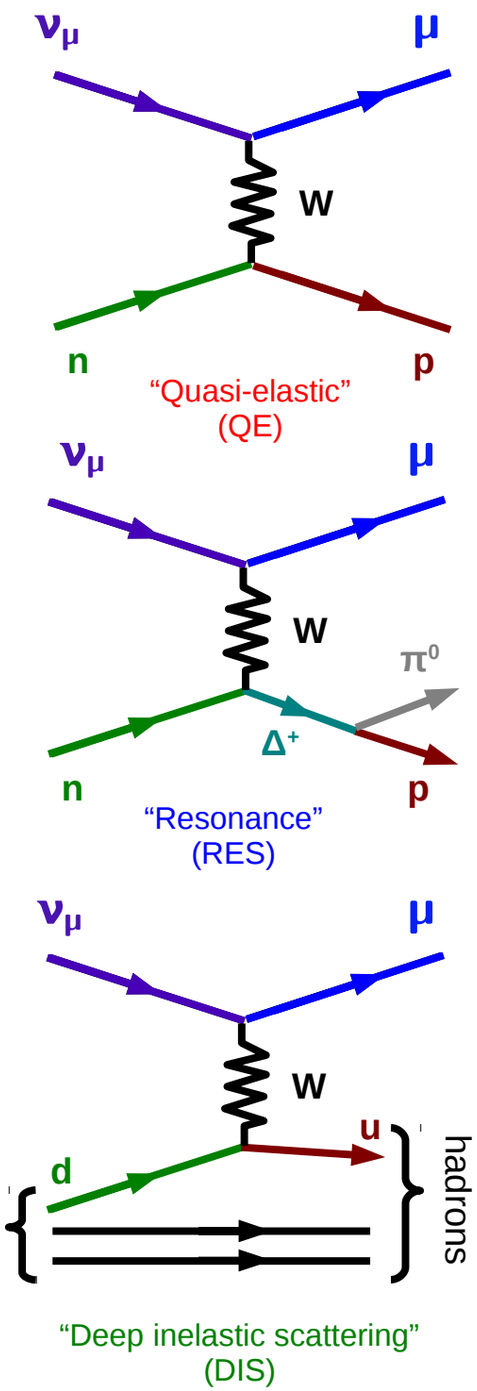
Numi Off-axis ν_e Appearance

- Long baseline neutrino experiment based at Fermilab.
- The main analyses use the oscillation channels:
  - $(\nu_\mu \rightarrow \nu_\mu)$, $(\nu_\mu \rightarrow \nu_e)$
  - $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$, $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Oscillation probabilities depend on ν energy.
- **ν energy reconstruction depends on knowledge of cross sections.**



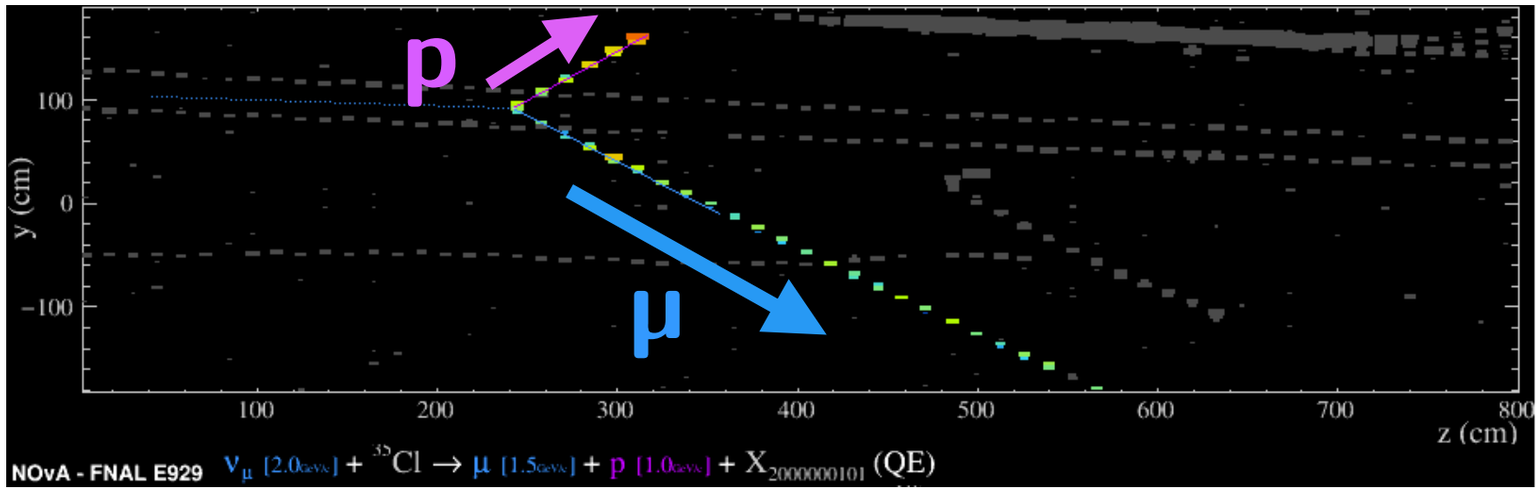
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2\theta_{23} \sin^2(\Delta m^2_{23} L/4E)$$

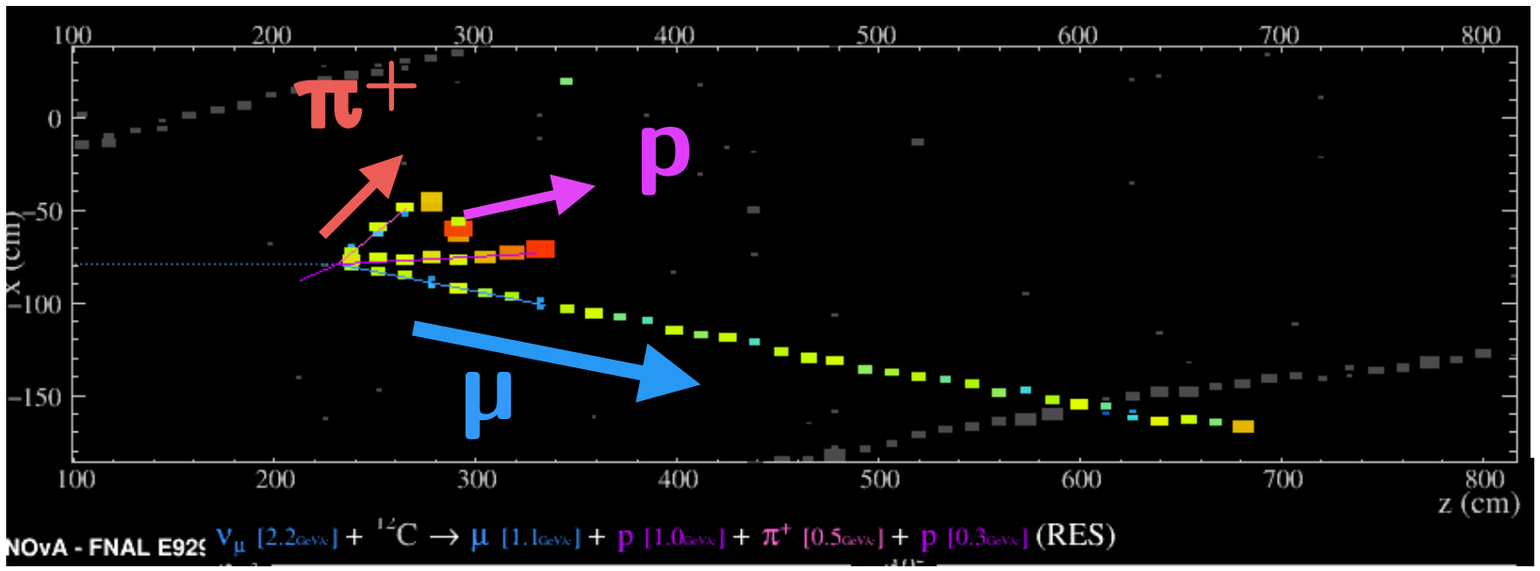
Charged current primary interactions



- ν energy reconstruction depends on knowledge of cross sections.

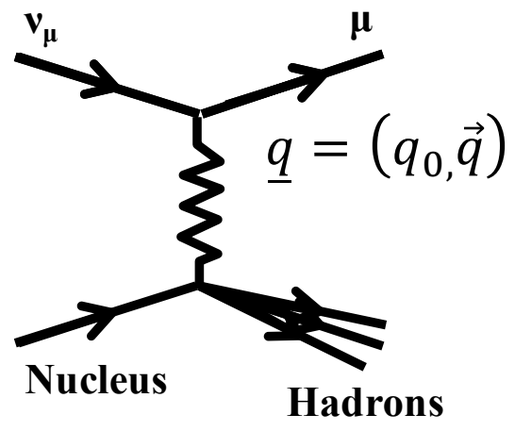
$$E_\nu = E_{lepton} + E_{had}$$



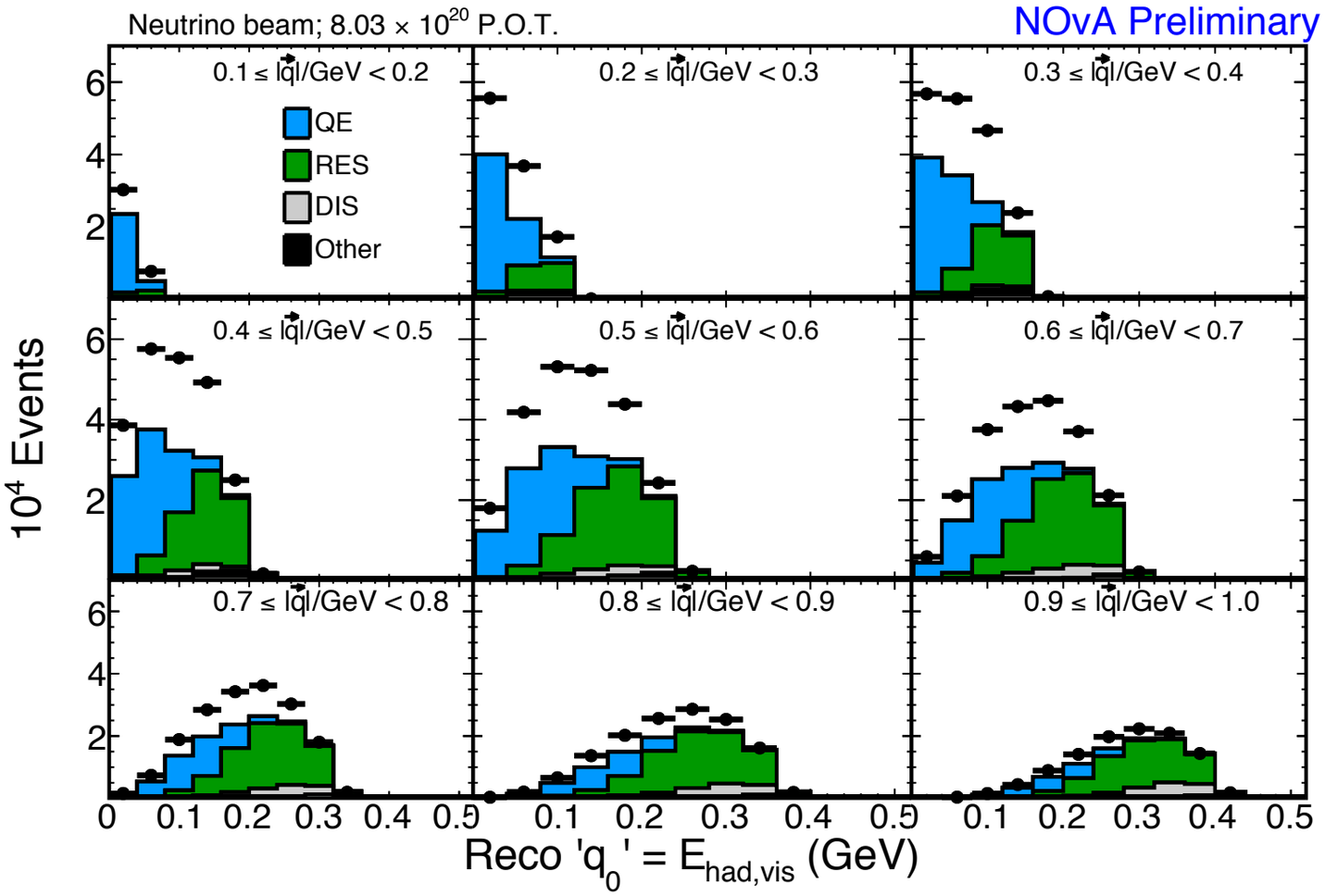


Most common free nucleus interactions

Simulating ν_μ CC interactions in the Near Detector (ND)

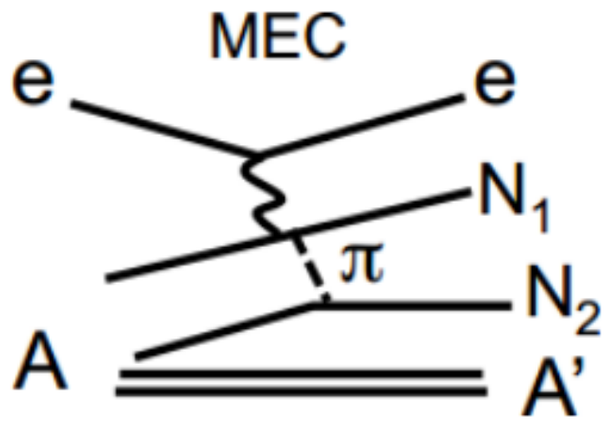


- The ν_μ charged current (CC) events in the ND are simulated with **default GENIE (2.12.2)** using the primary interaction models: QE, RES, DIS.
- Clear simulation deficit at the intermediate values of reconstructed hadronic energy q_0 and transferred momentum $|q|$.

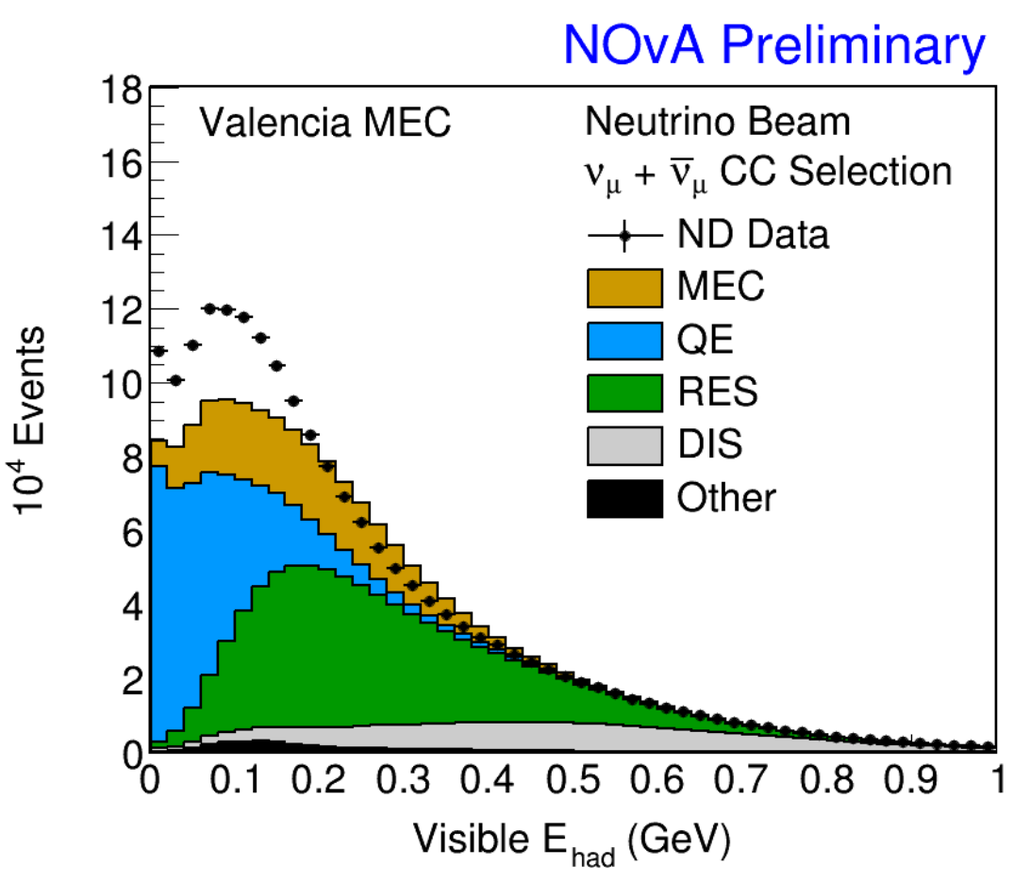


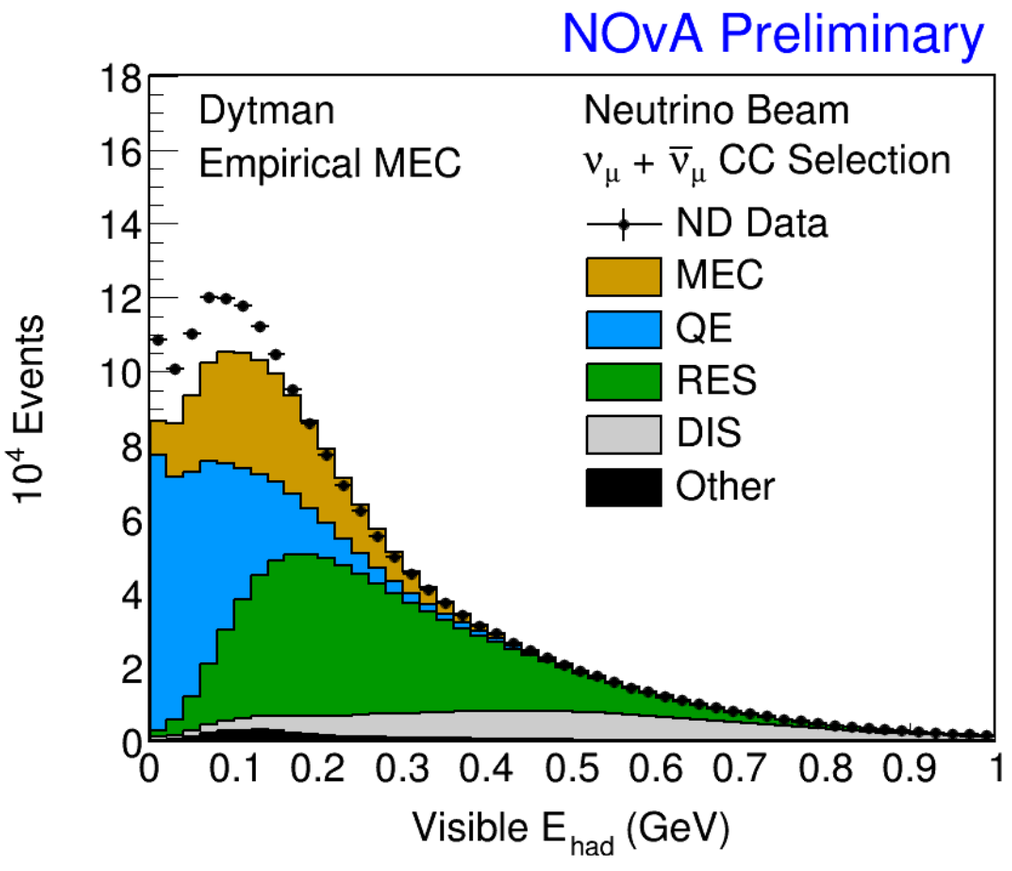
Addressing the missing events

- Additional nuclear effects first observed in electron scattering also thought to contribute to multinuclear emission processes for neutrinos, such as two-particle two-hole (**2p2h**) Meson Exchange Current (**MEC**).
  - Not fully understood
- Different models include interactions in the phase space of interest: **Valencia MEC** and **Dytman Empirical MEC** in GENIE.
- We tune **Dytman Empirical MEC** to NOvA ND data in the (q_0, $|q|$).



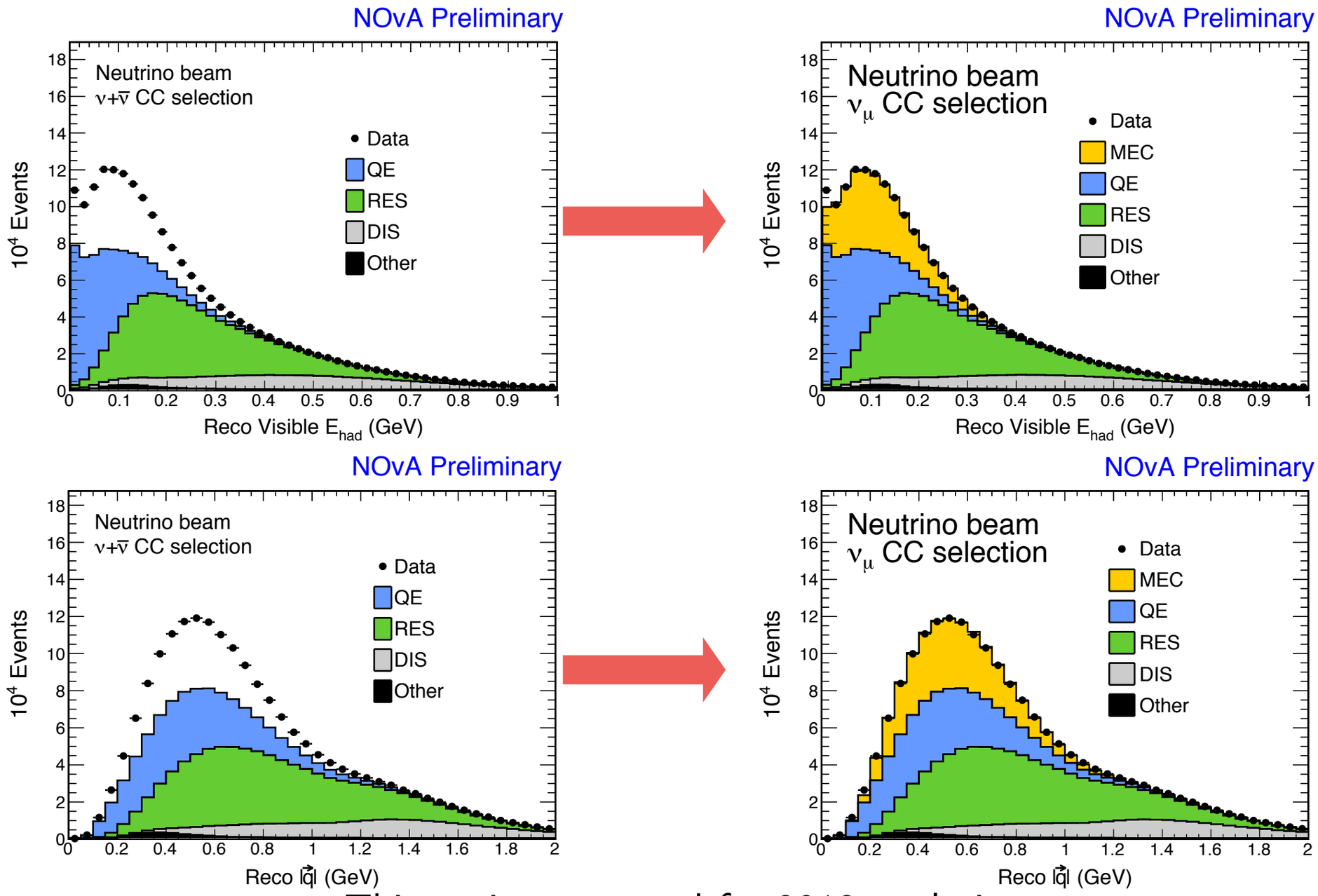
From G.D. Megias, NuFact 2015





Neutrino cross section model

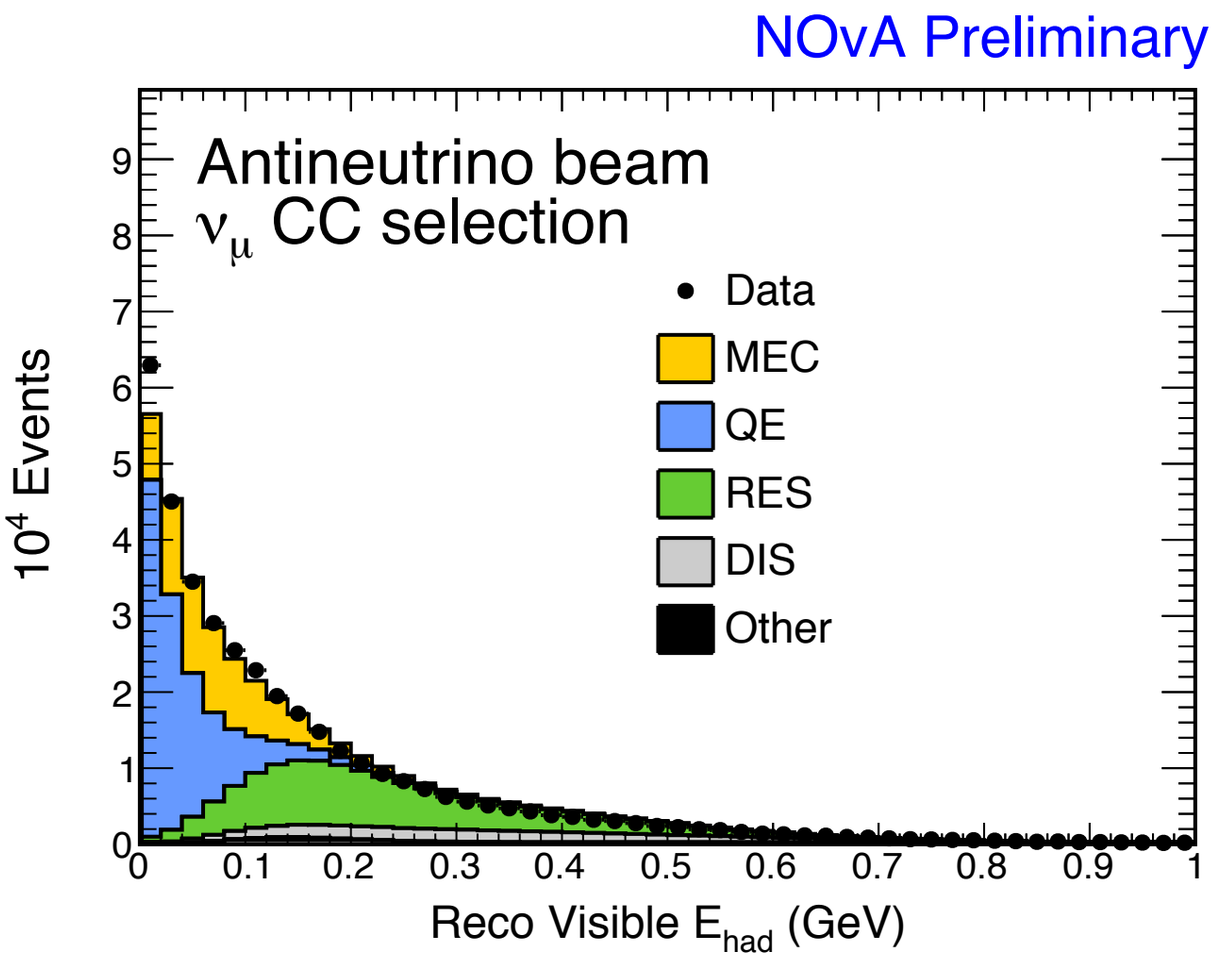
- We fit the 2p2h (MEC) sample simultaneously in true (q_0,$|\mathbf{q}|$) space by optimizing the agreement of the simulation to the data in the corresponding reconstructed variables.
- This yields a set of weights for the MEC events.

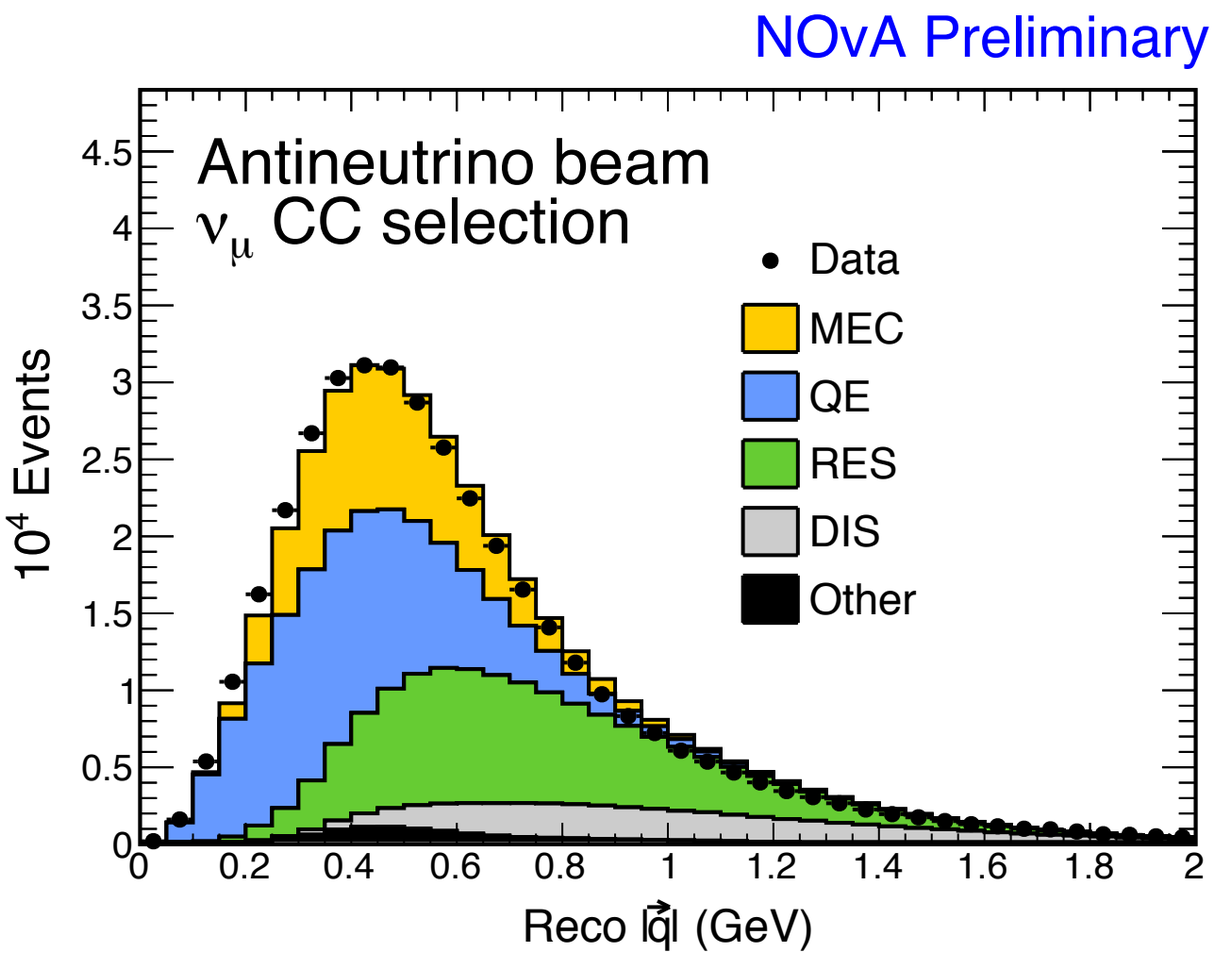


- This tuning was used for 2018 analysis.

Antineutrino cross section model

- We currently tune the cross section models for the neutrino beam and antineutrino beam data sets separately.
- The same procedure is used for both but the wrong-sign background in the antineutrino data set uses the neutrino-based weights.





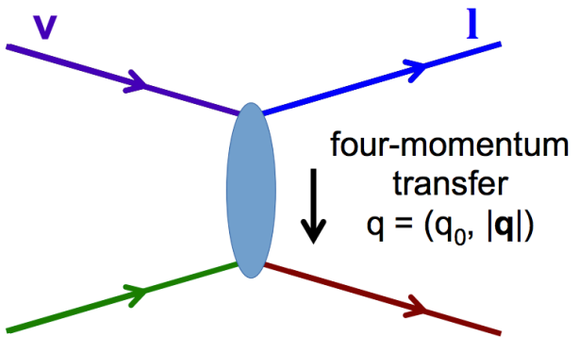
Studying data by prong multiplicity

- We can further study the cross section model tune by splitting the data into subsets of different multiplicity (i.e. number of reconstructed prongs).
    - A prong is a cluster of hits grouped into a single object. The hadronic shower energy depositions can be reconstructed as multiple prongs.

# of prongs	ν beam data	$\bar{\nu}$ beam data
1	40%	47%
2	38%	36%
3	14%	11%
4+	8%	6%

- Most of the ν_μ selected data is reconstructed with one or two prongs (78% for neutrinos and 83% for antineutrinos).

Studying prong multiplicity in neutrino beam

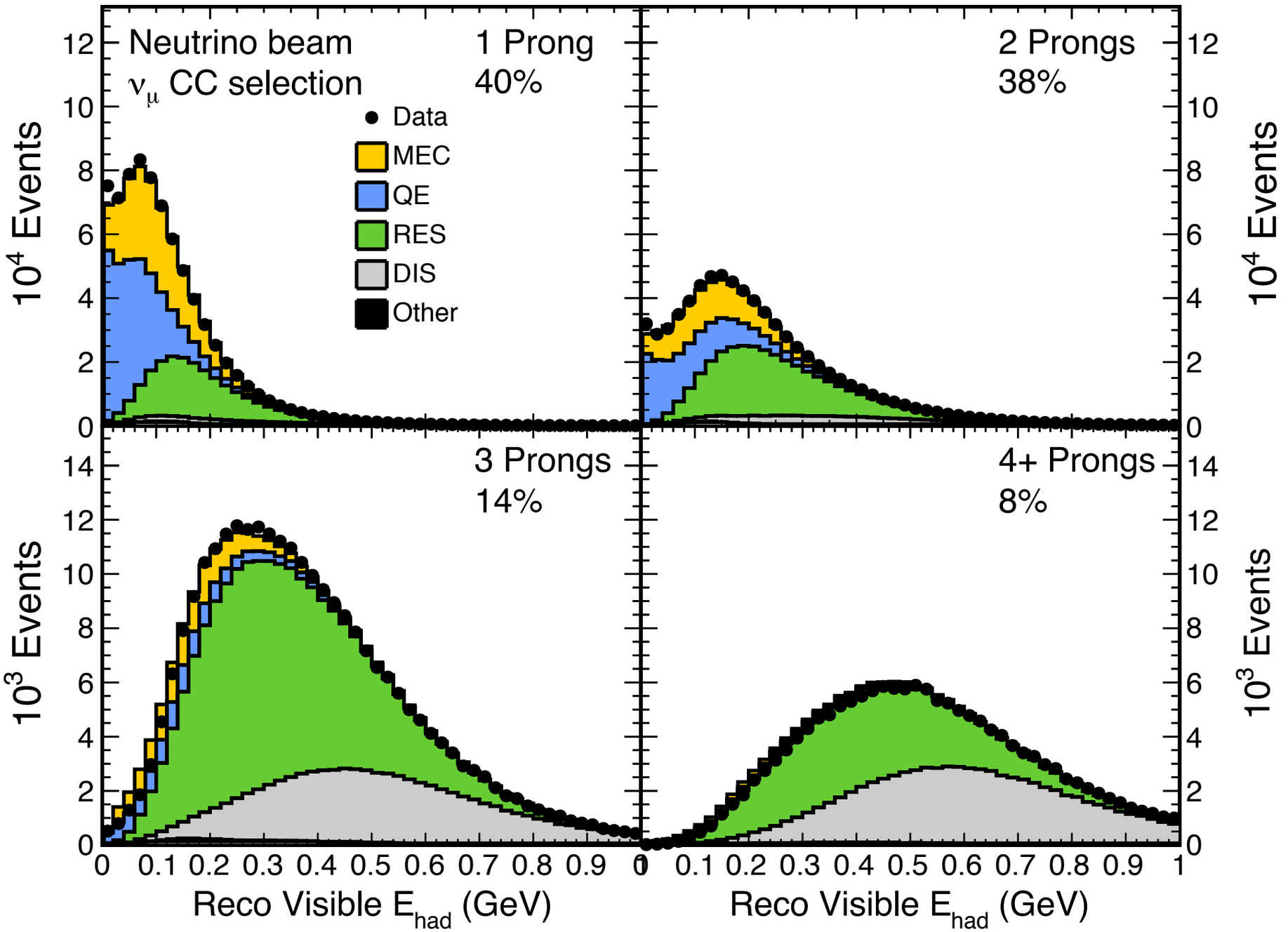


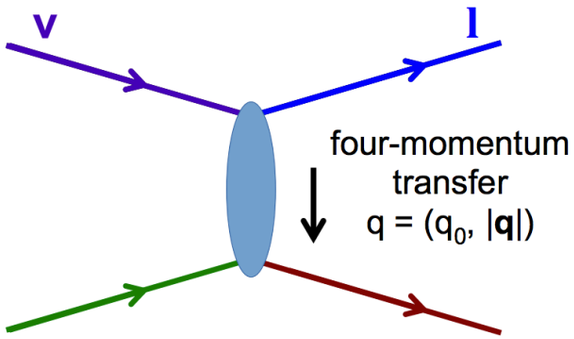
Reconstructed visible hadronic energy

Excellent agreement in all the multiplicity bins

The high multiplicity bins also isolate RES and DIS.

NOvA Preliminary





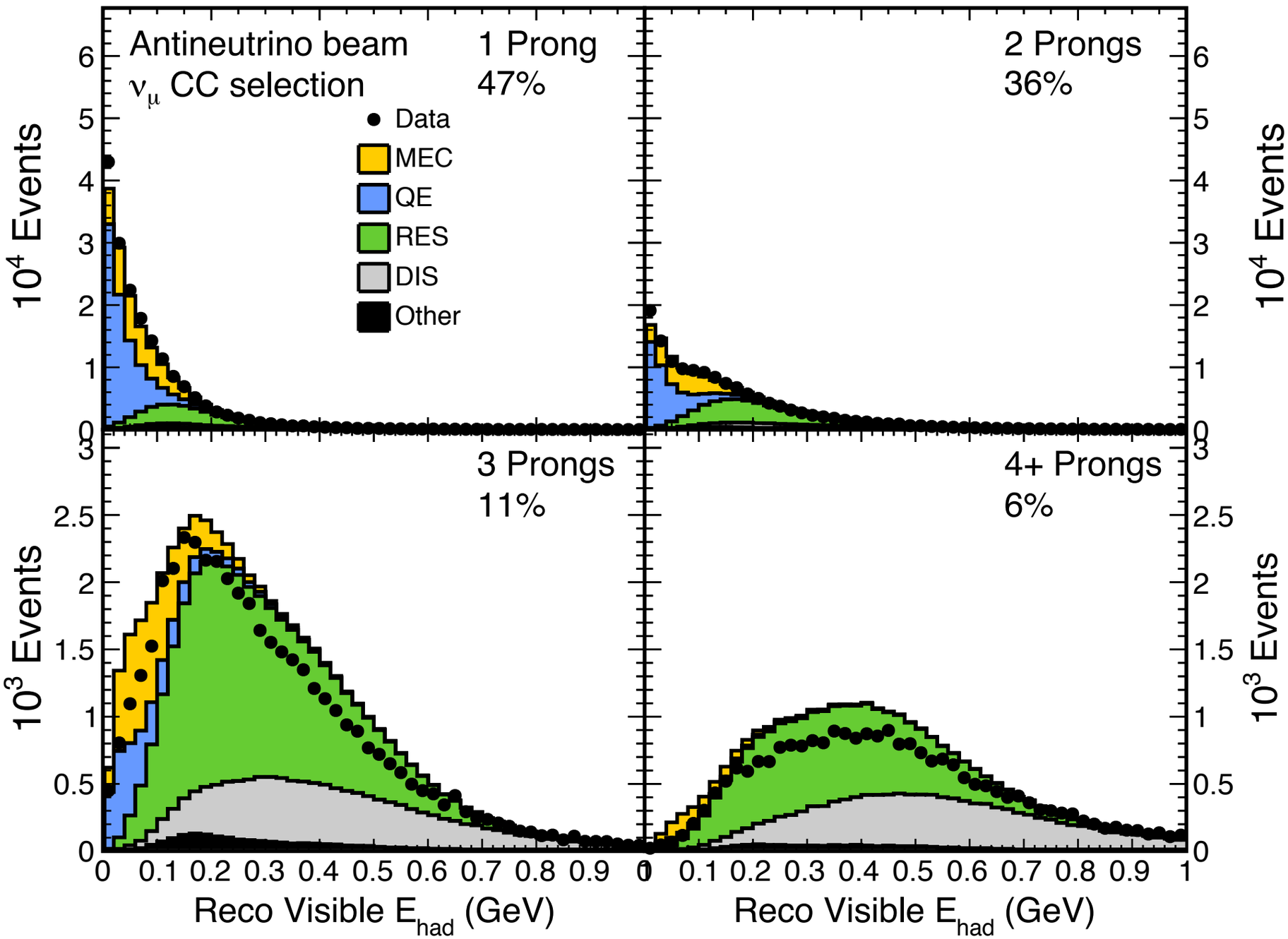
Studying prong multiplicity in antineutrino beam

NOvA Preliminary

Reconstructed visible hadronic energy

Simulation deficit in low multiplicity and excess in higher multiplicity

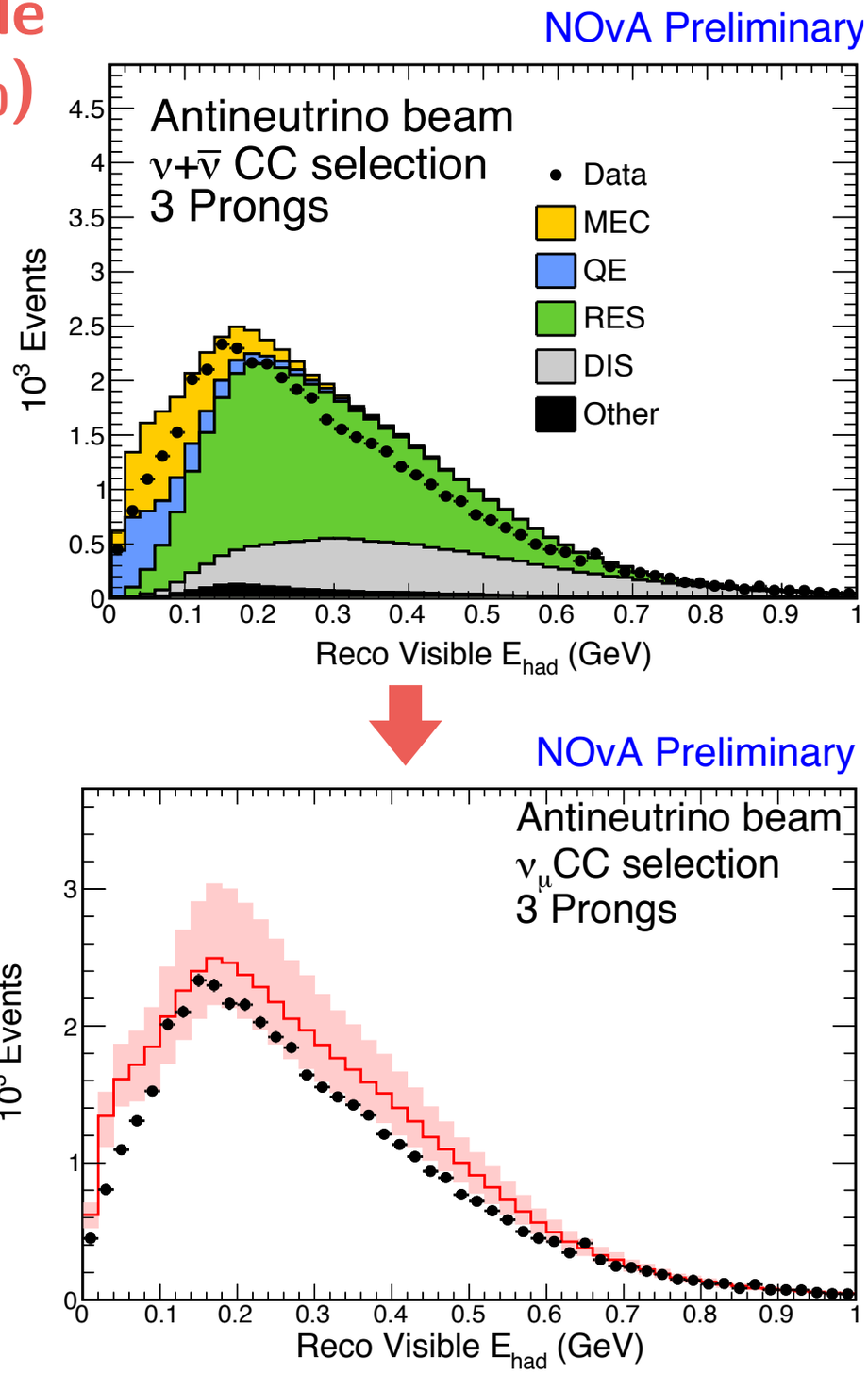
- Note high multiplicity samples together are only 17% of the total antineutrino selected data.

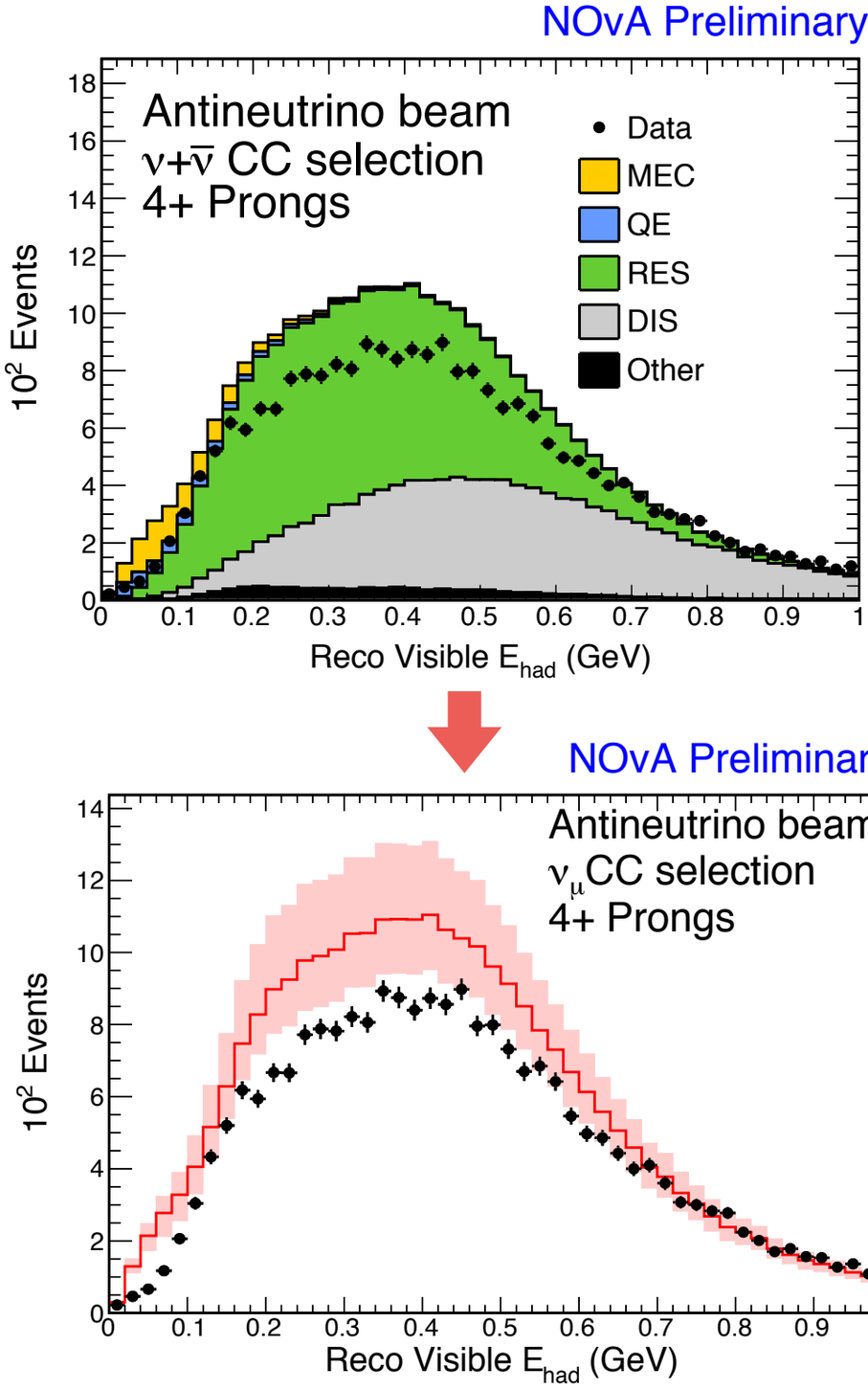


High prong multiplicity in antineutrino beam

Reconstructed visible hadronic energy (q_0)

- For the high multiplicity (3+) samples the data lies at the edge of the estimated cross section systematic uncertainties.



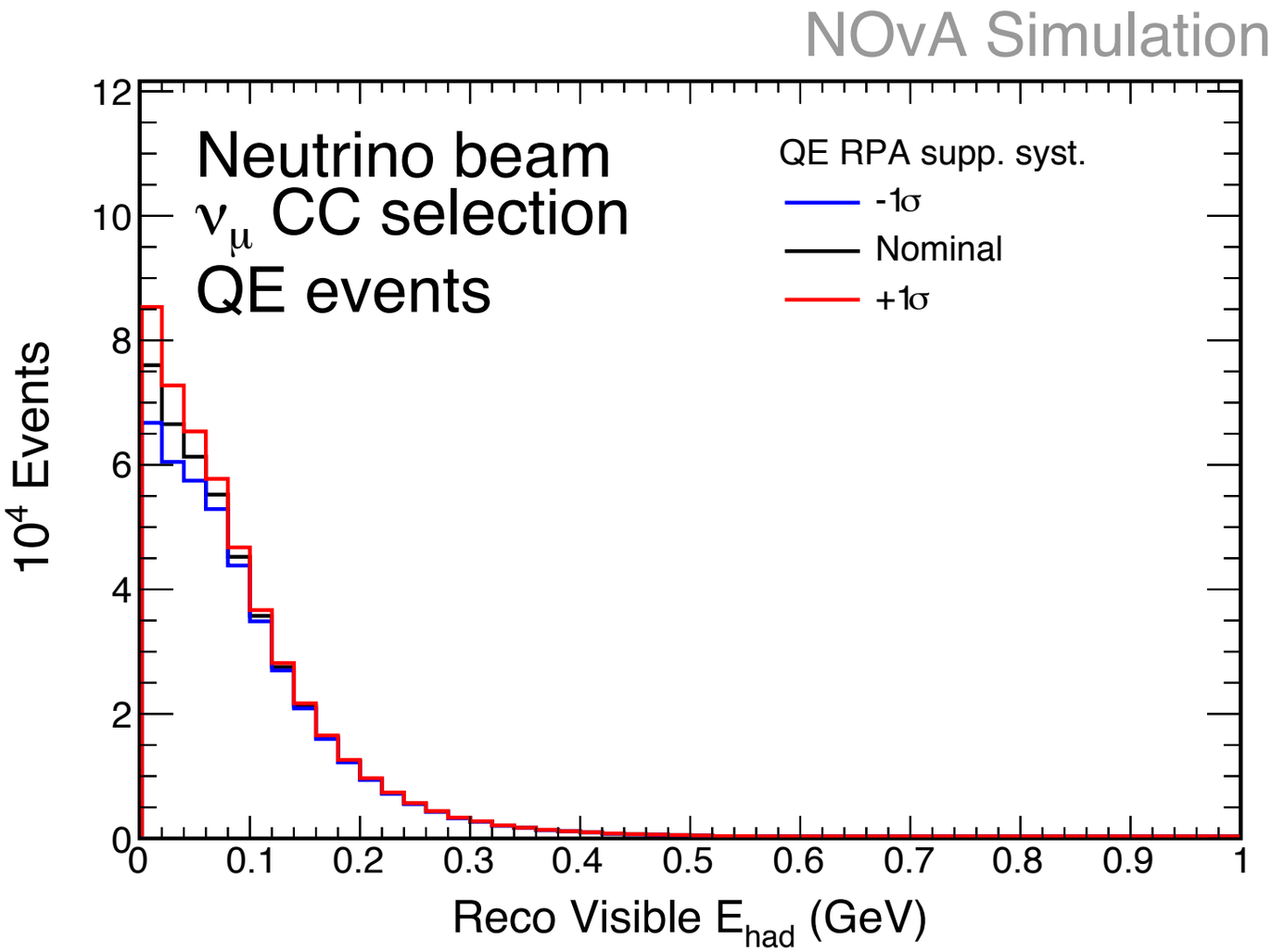


Next: Tuning simultaneously neutrinos and antineutrinos

- Good agreement in kinematic variables and for different multiplicities: only at the high multiplicity samples the model shows some tension with data.

- We are investigating using a simultaneous tuning procedure for both neutrino and antineutrino data:

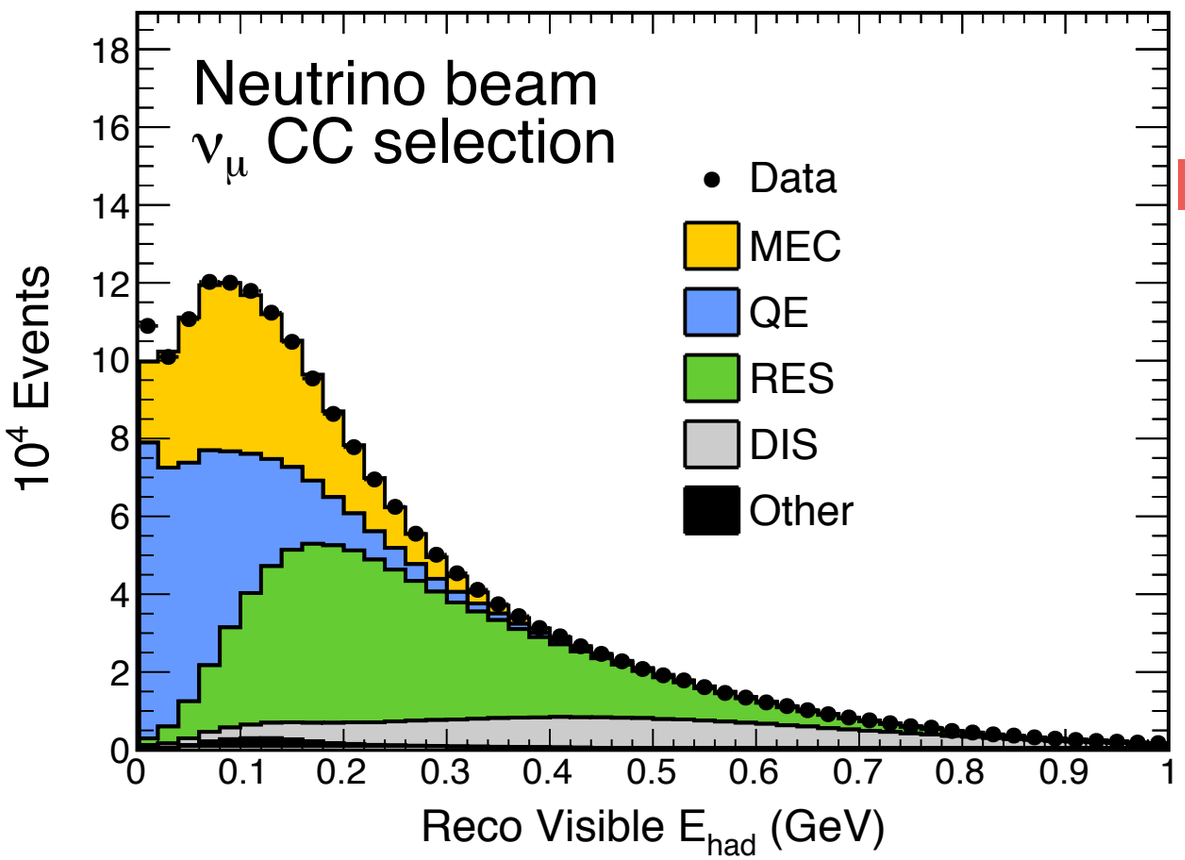
  - This must take into account systematic uncertainties. In particular for this attempt we take into consideration **QE RPA shape suppression.**



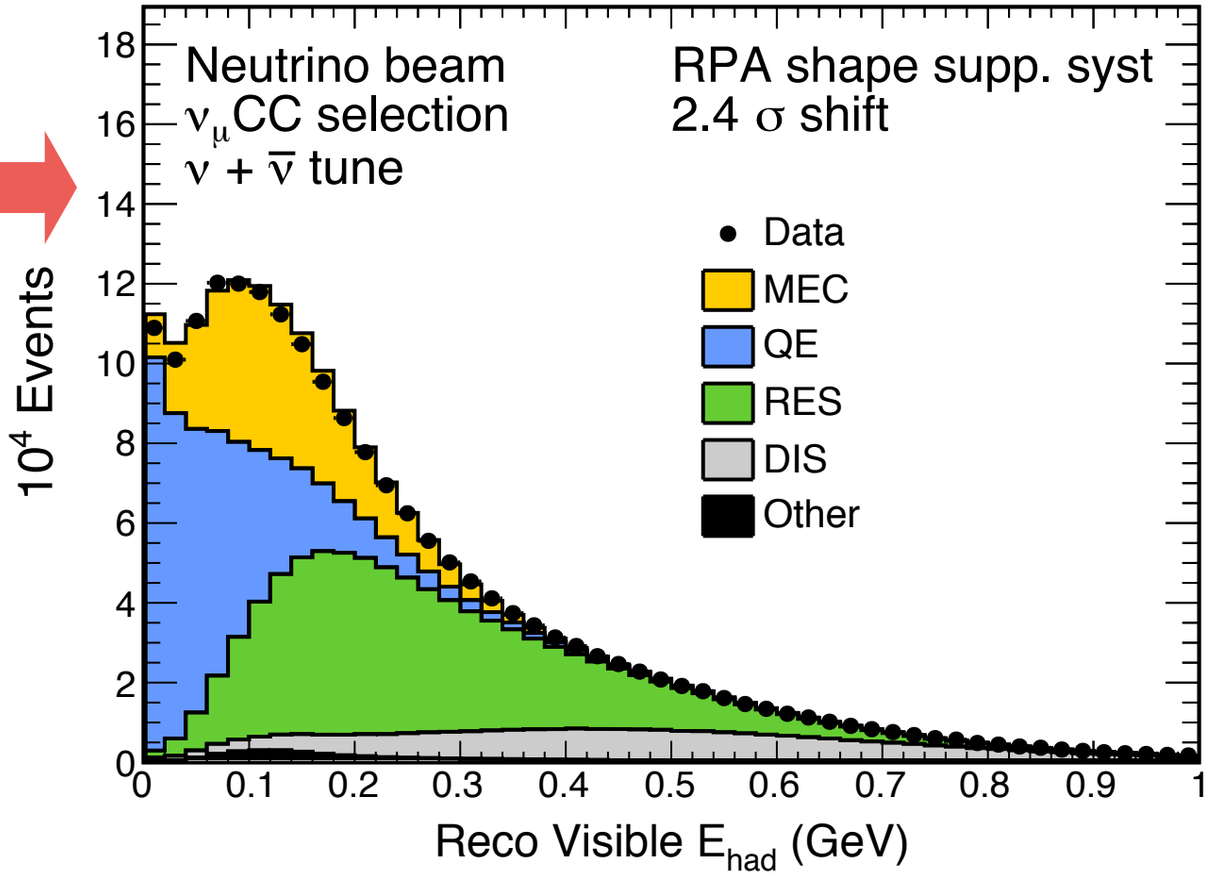
Joint tuning of neutrinos and antineutrinos: Neutrino data

- We tune the MEC events optimizing the agreement in q_0 and $|\mathbf{q}|$ for both the neutrino and antineutrino datasets.
- Including the **QE RPA shape suppression** systematic shift as a fit parameter corrects for the disagreement in the first bin of visible hadronic energy by shifting the QE events.

NOvA Preliminary



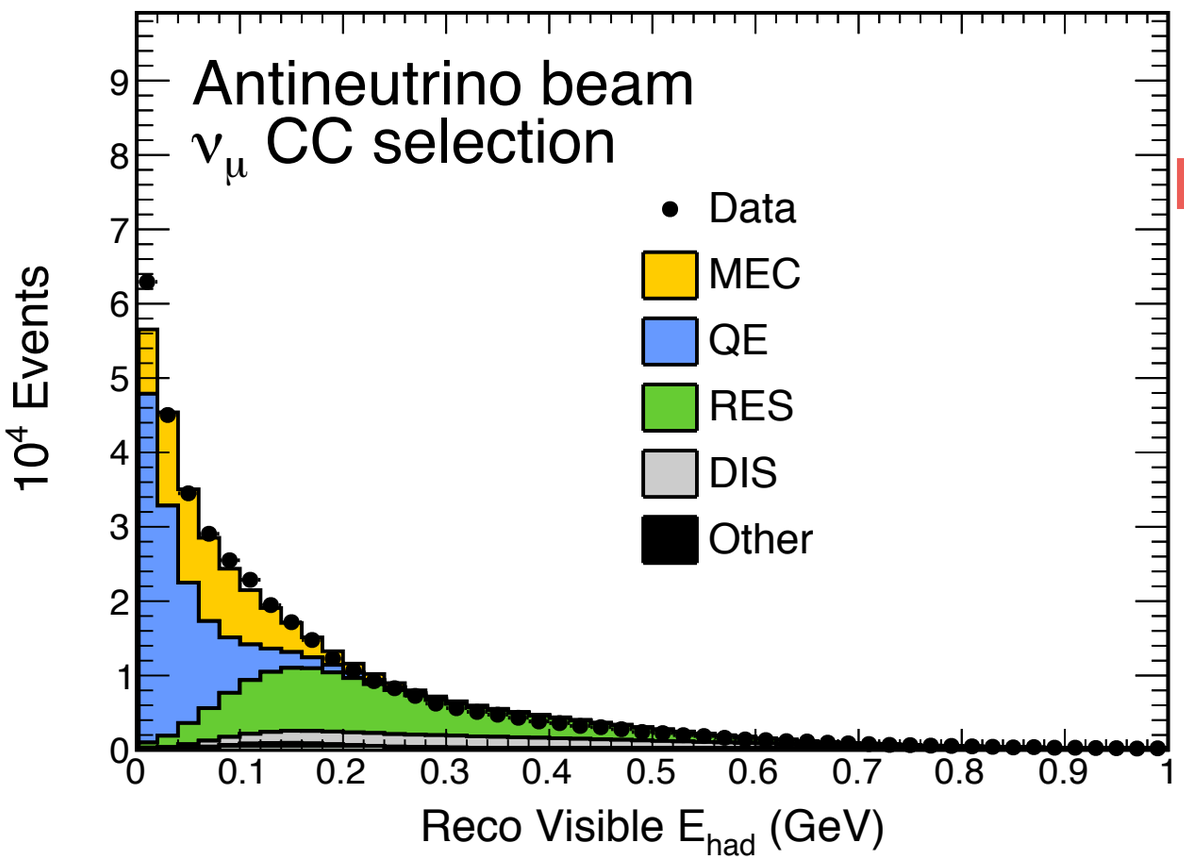
NOvA Preliminary



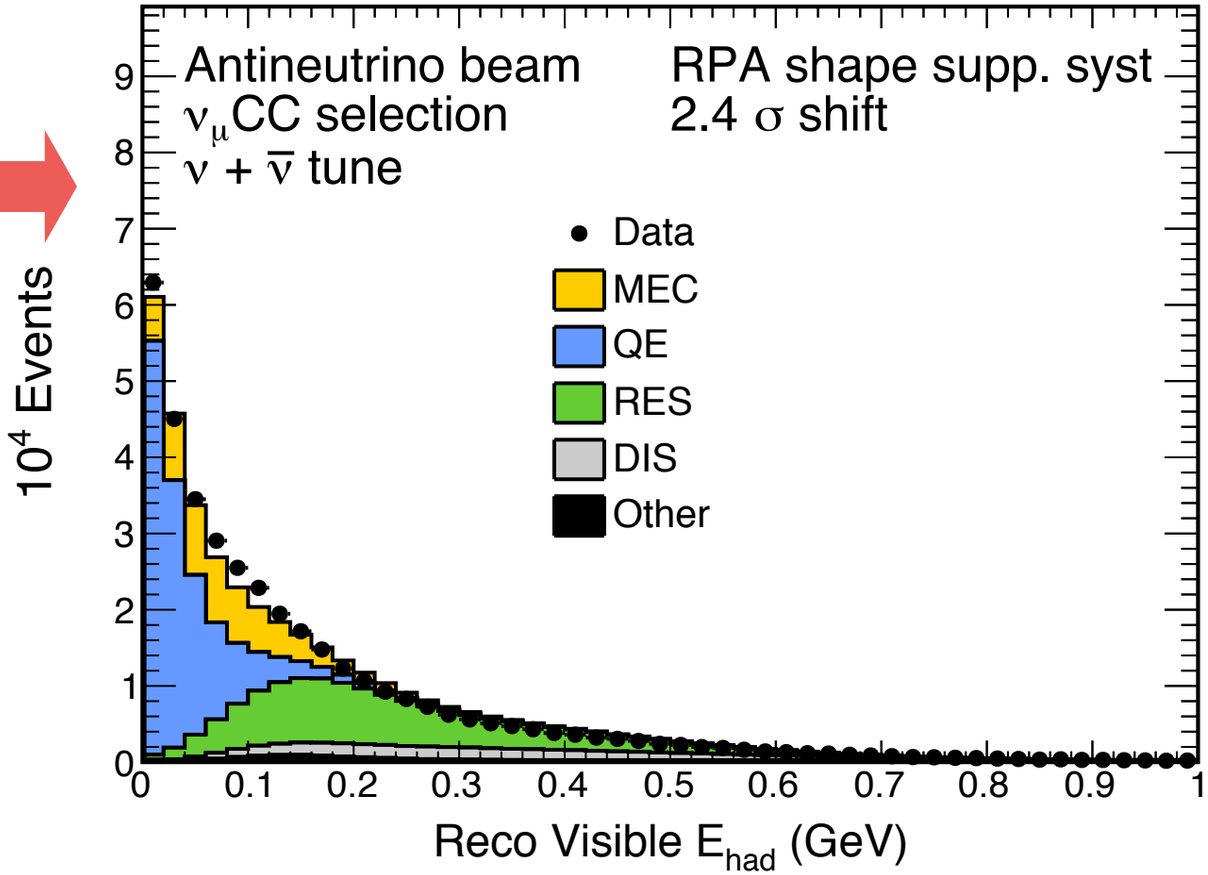
Joint tuning of neutrinos and antineutrinos: Antineutrino data

- We tune the MEC events optimizing the agreement in q_0 and $|\mathbf{q}|$ for both the neutrino and antineutrino datasets.
- Including the **QE RPA shape suppression** systematic shift as a fit parameter corrects for the disagreement in the first bin of visible hadronic energy by shifting the QE events.

NOvA Preliminary



NOvA Preliminary



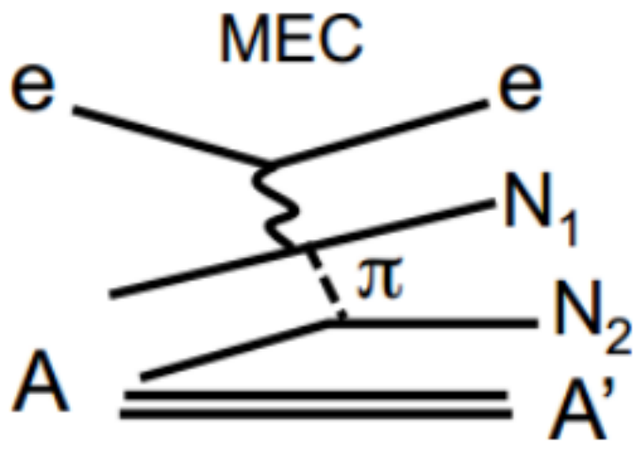
Summary

- A simultaneous tune is feasible and shows reasonably good agreement with less parameters.
- NOvA's cross section tuning using an empirical 2p2h model shows good agreement in a number of kinematic variables and breakdown by prong multiplicity.
- Future work: add selected prong multiplicity and topology samples to the tune, include a more detailed set of systematic uncertainties and use different neutrino interaction models.

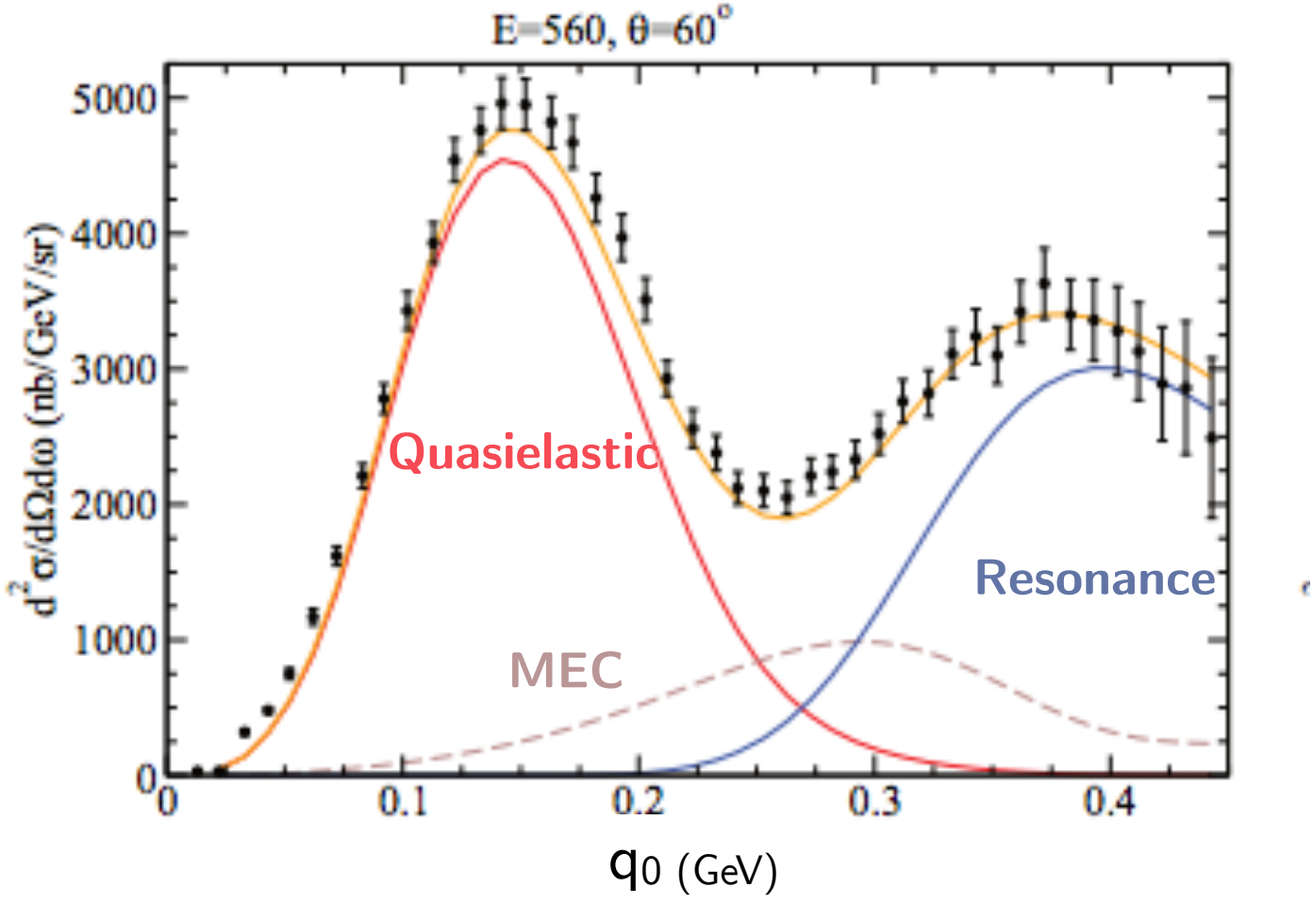
Backup

2p2h Meson Exchange Current

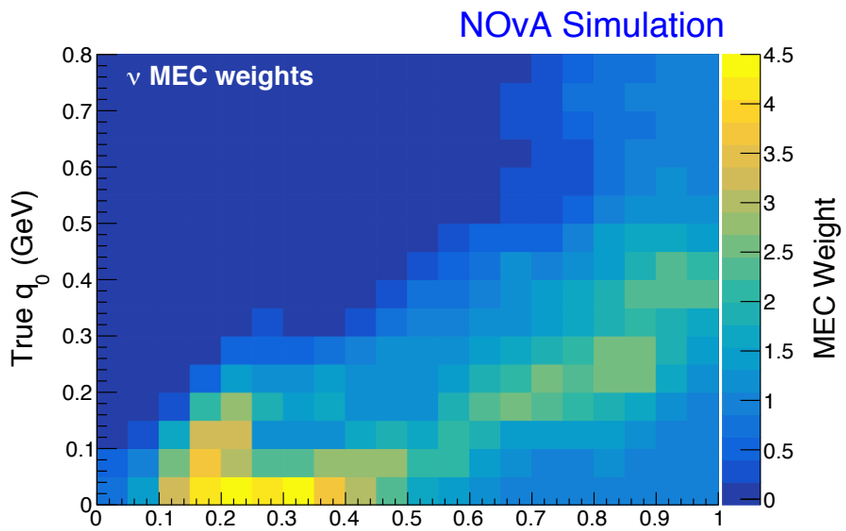
- Two-particle two-hole MEC observed in electron scattering data.
- Two nucleon ejection process where a weak boson is exchanged by a pair of nucleons in the kinematic region between quasi elastic and resonance cross section.

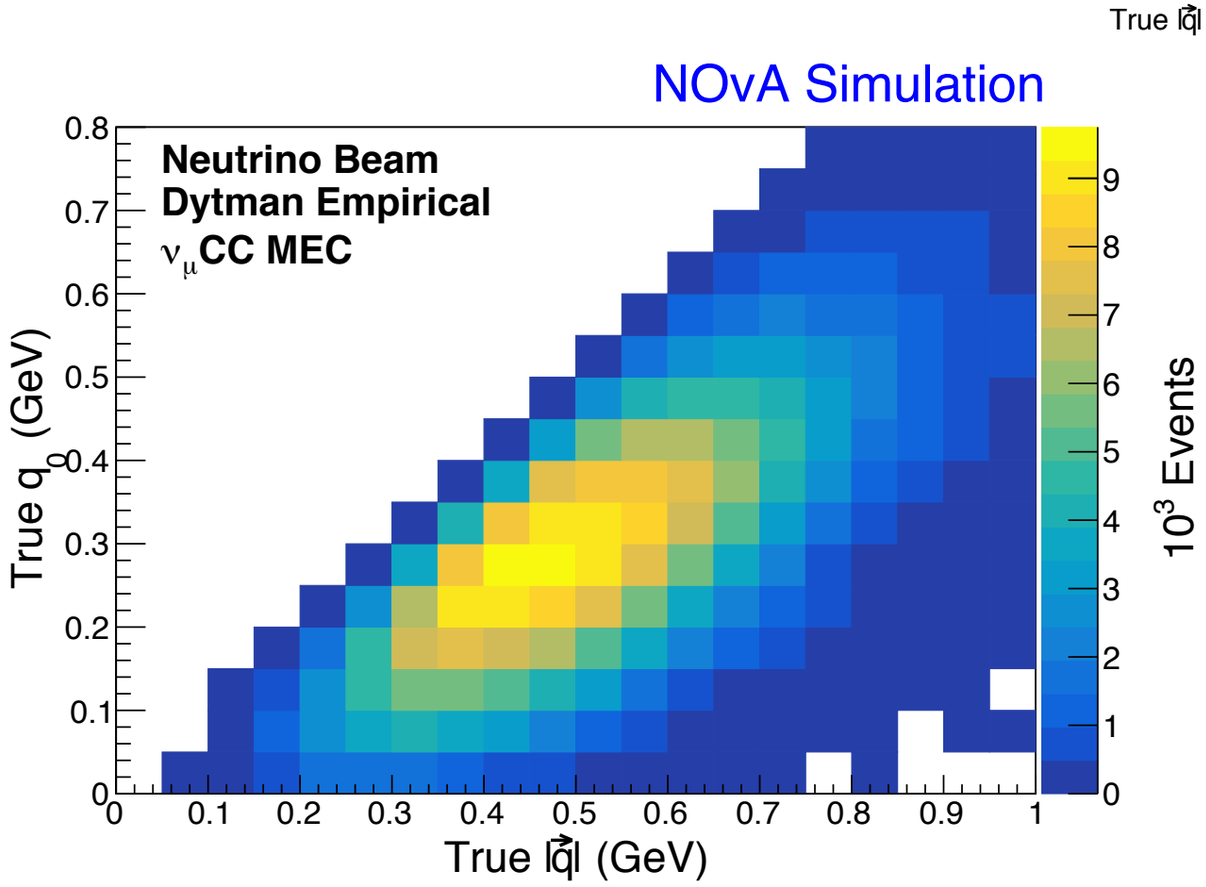


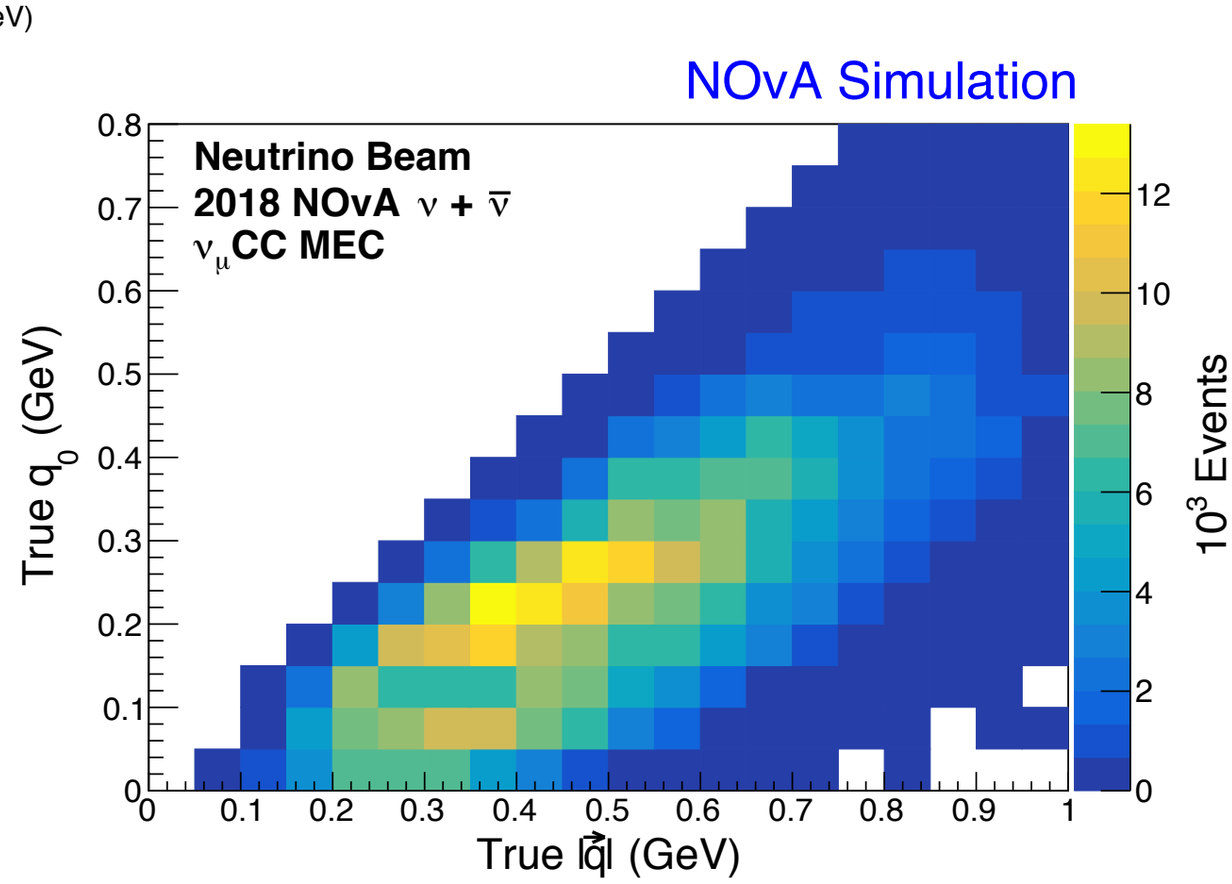
Adapted from G.D. Megias, NuFact 2015



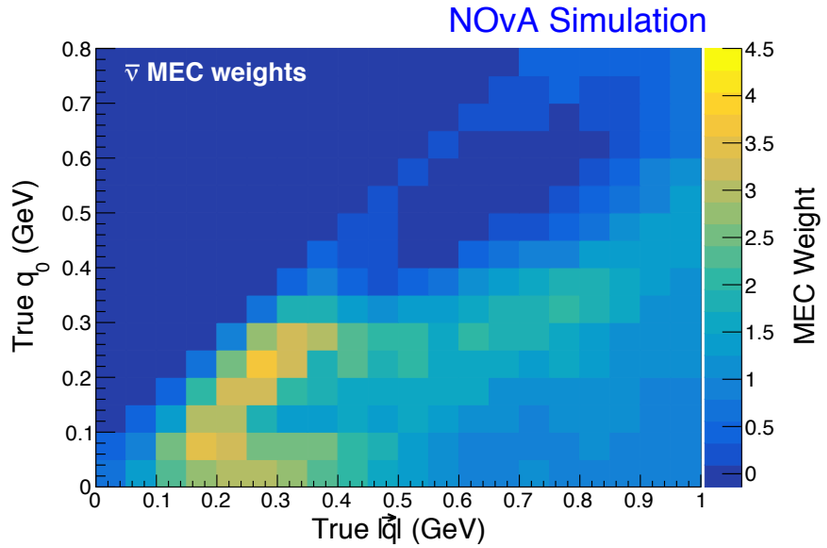
2d distributions of the cross section tune: neutrinos

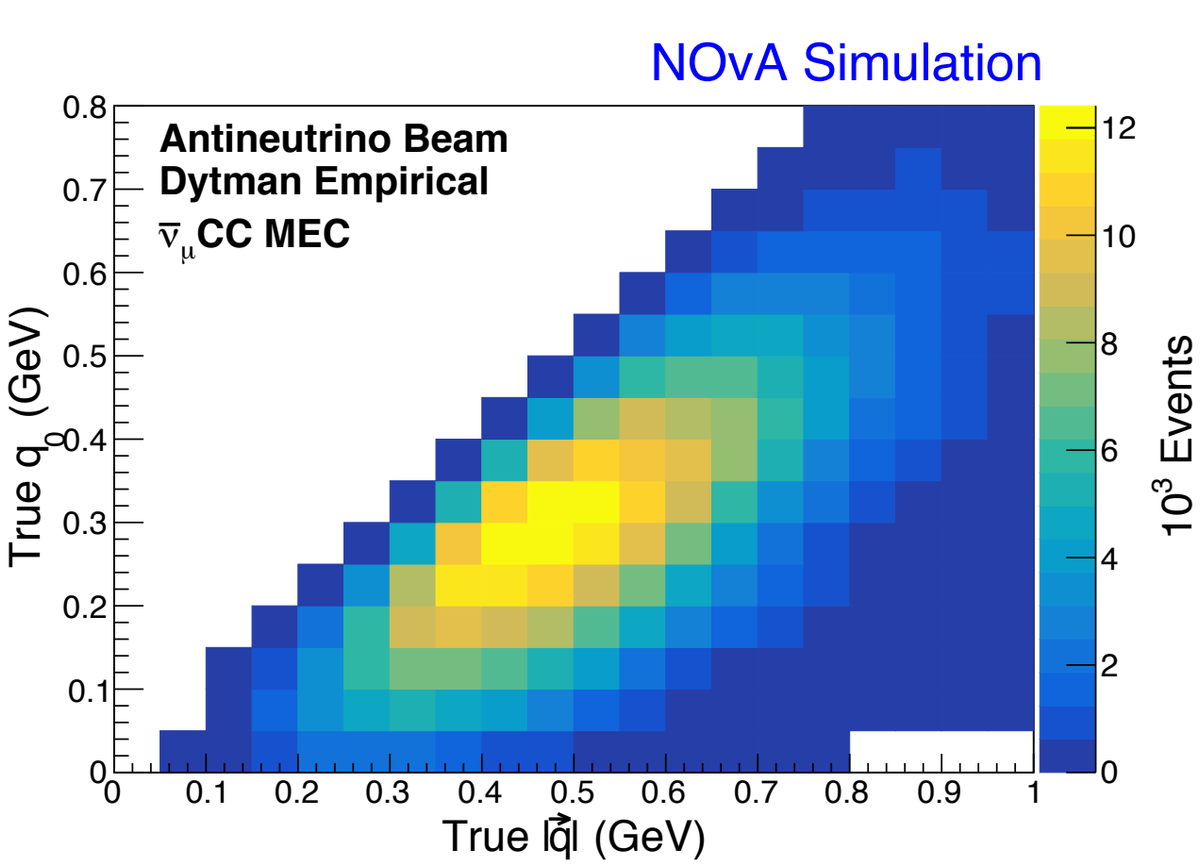


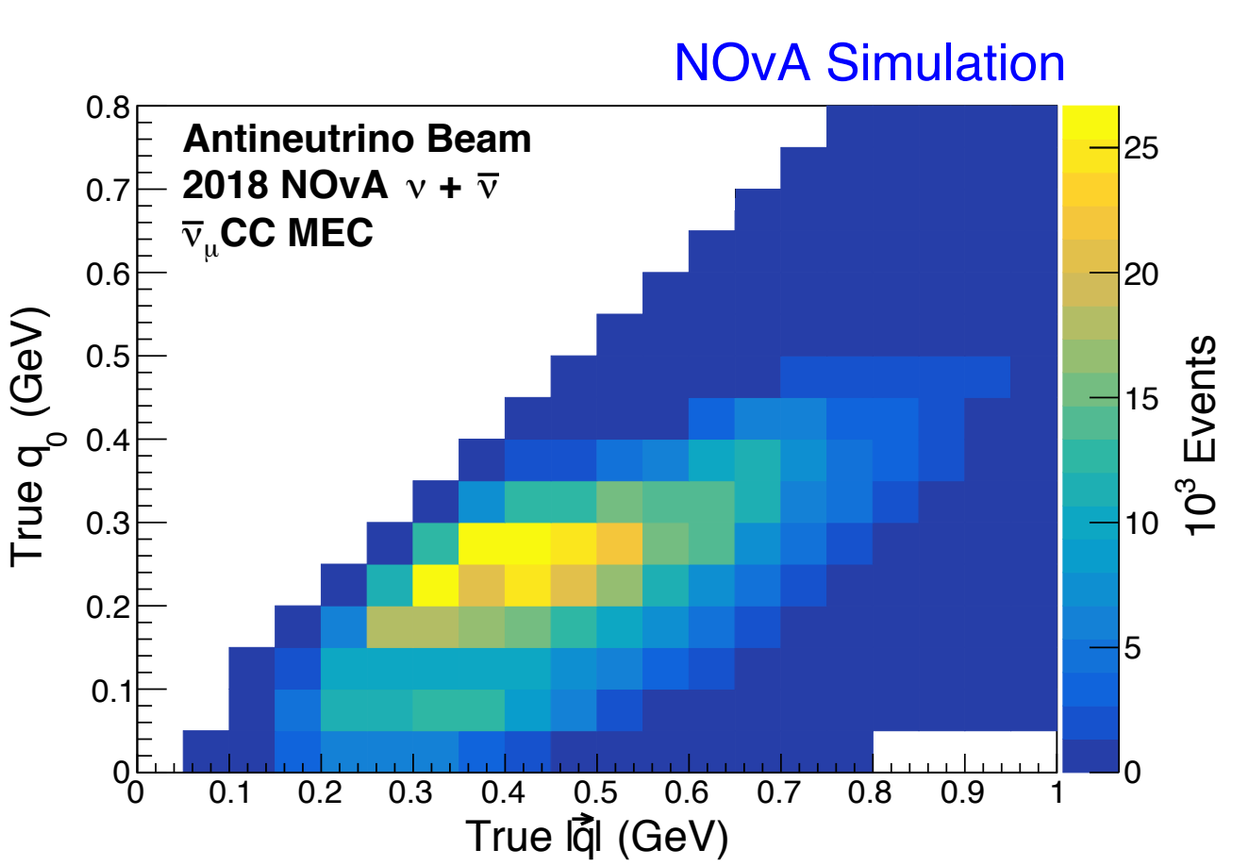




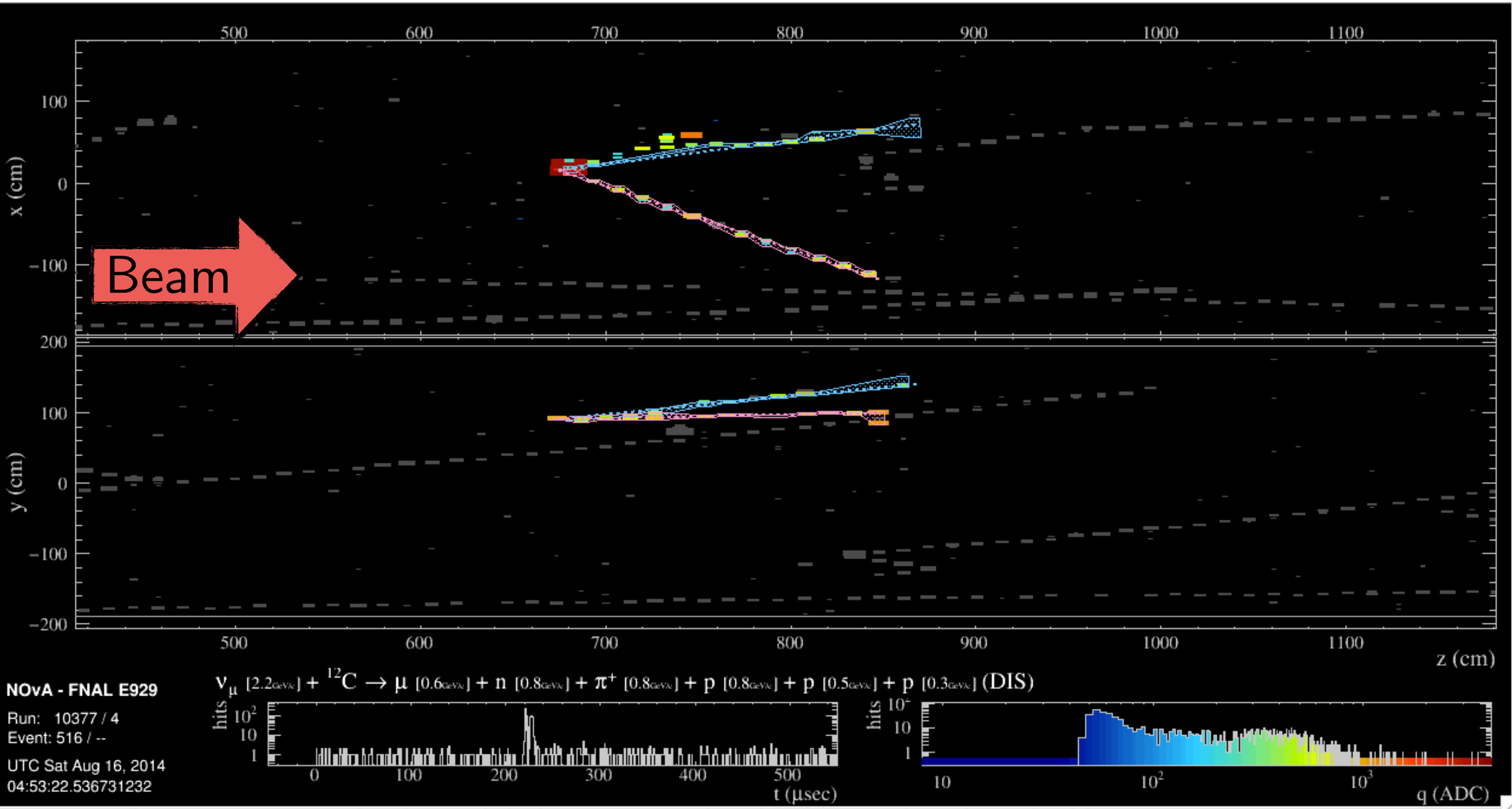
2d distributions of the cross section tune: antineutrinos





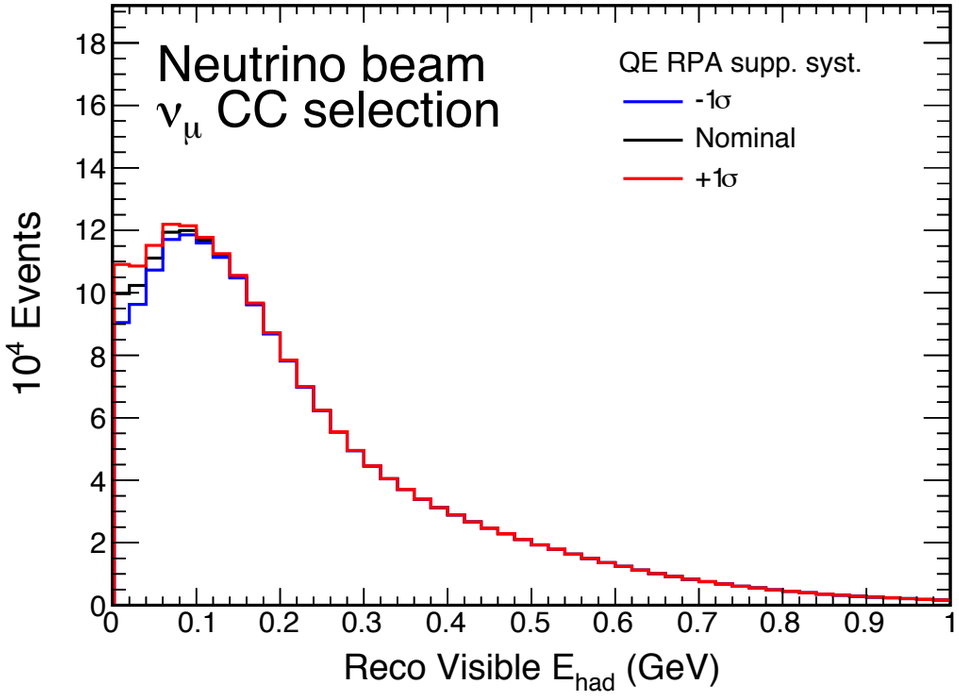


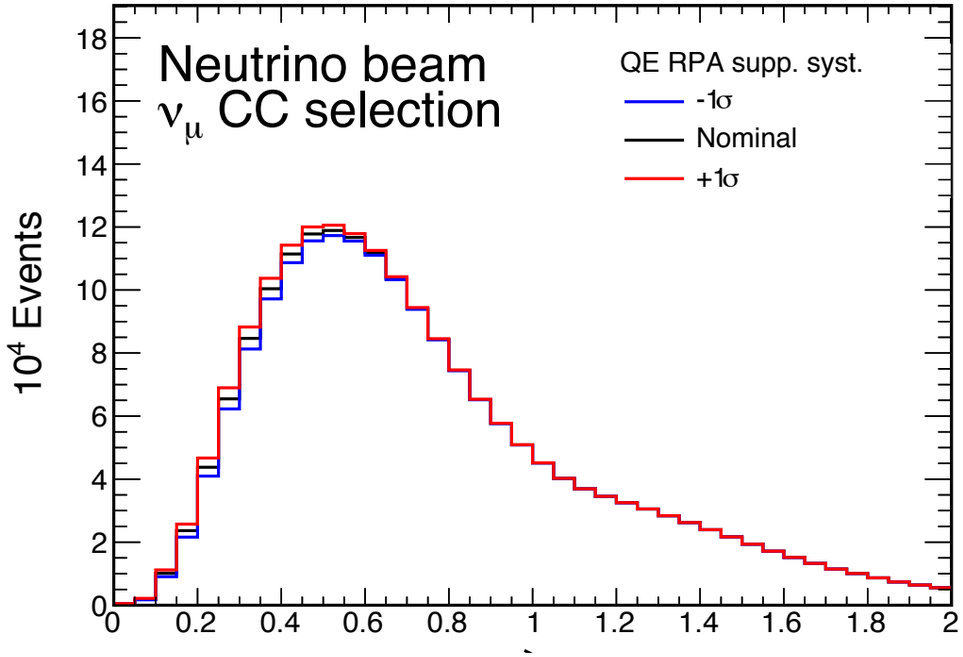
Studying data by prong multiplicity

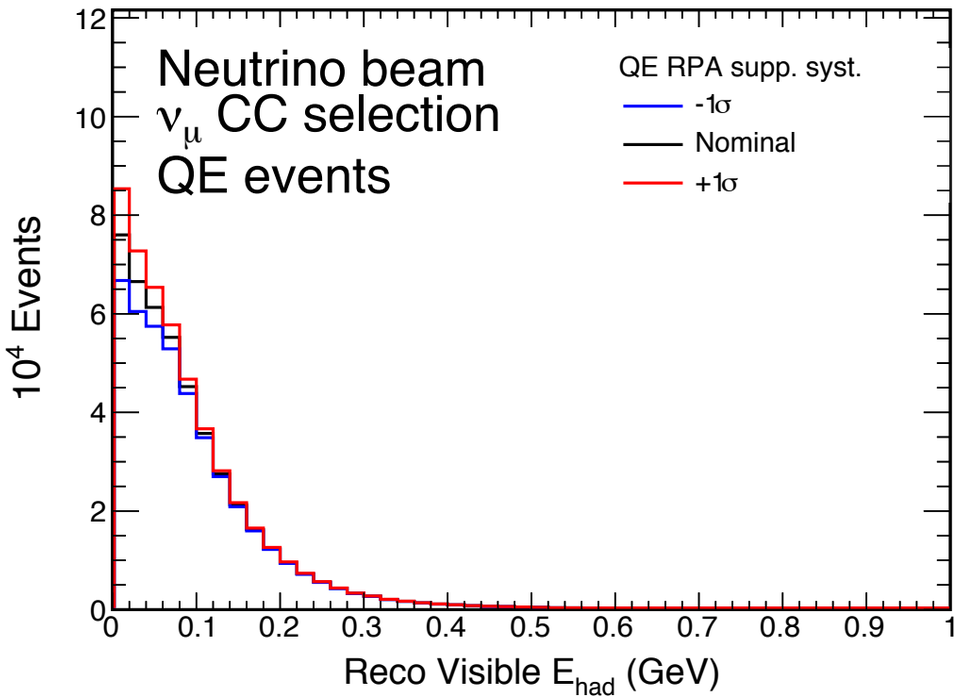


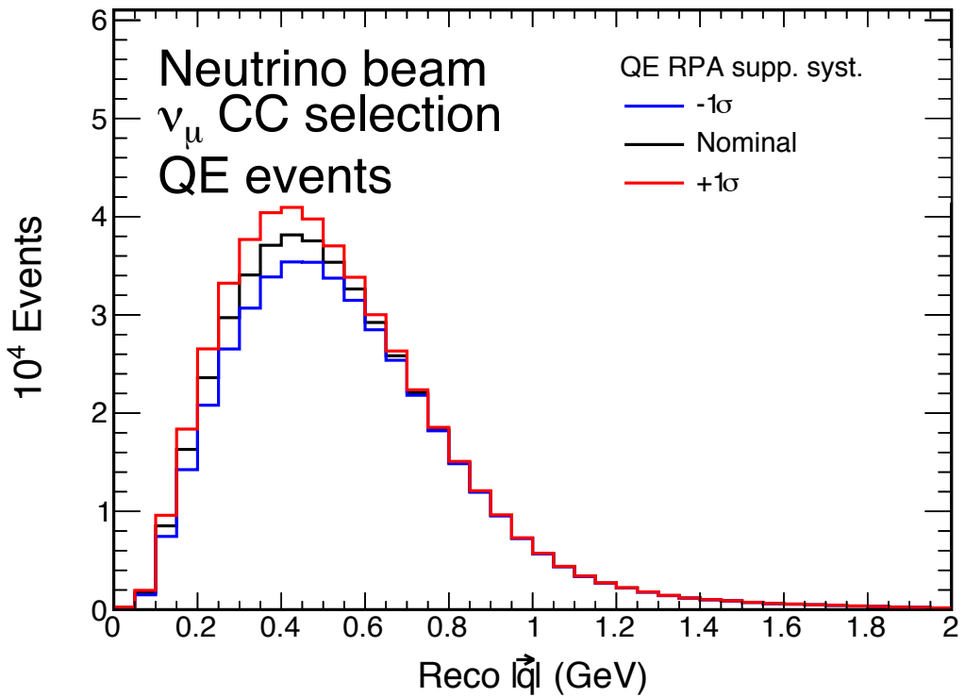
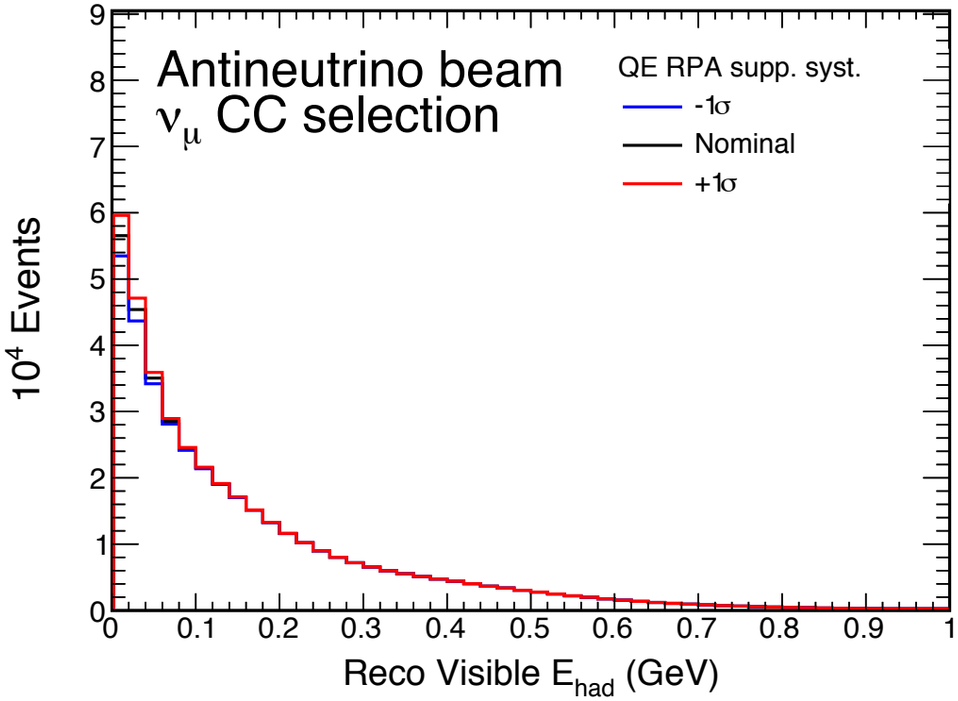
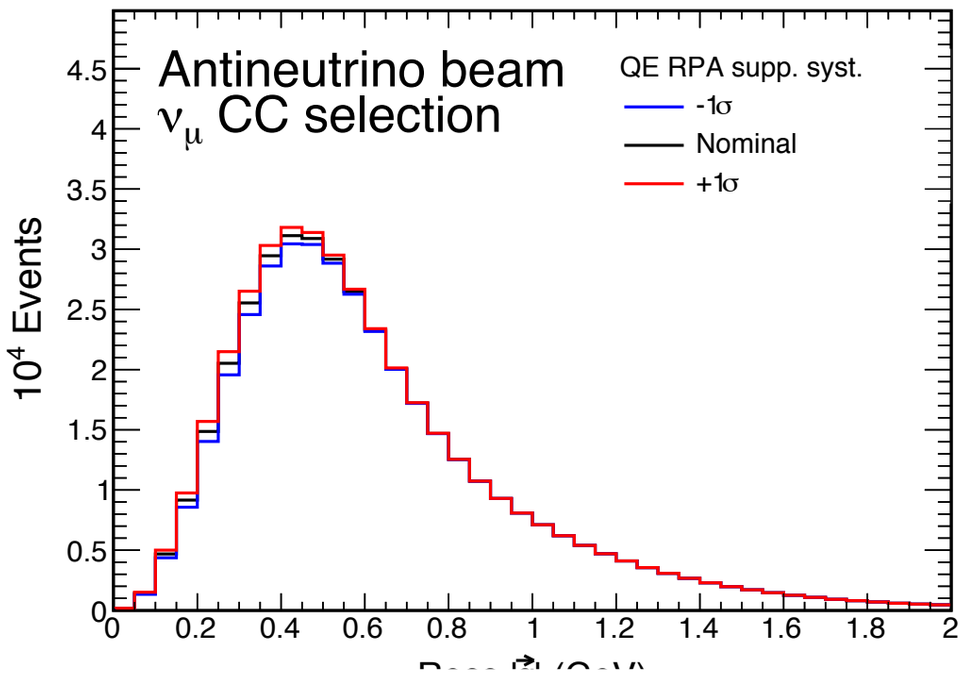
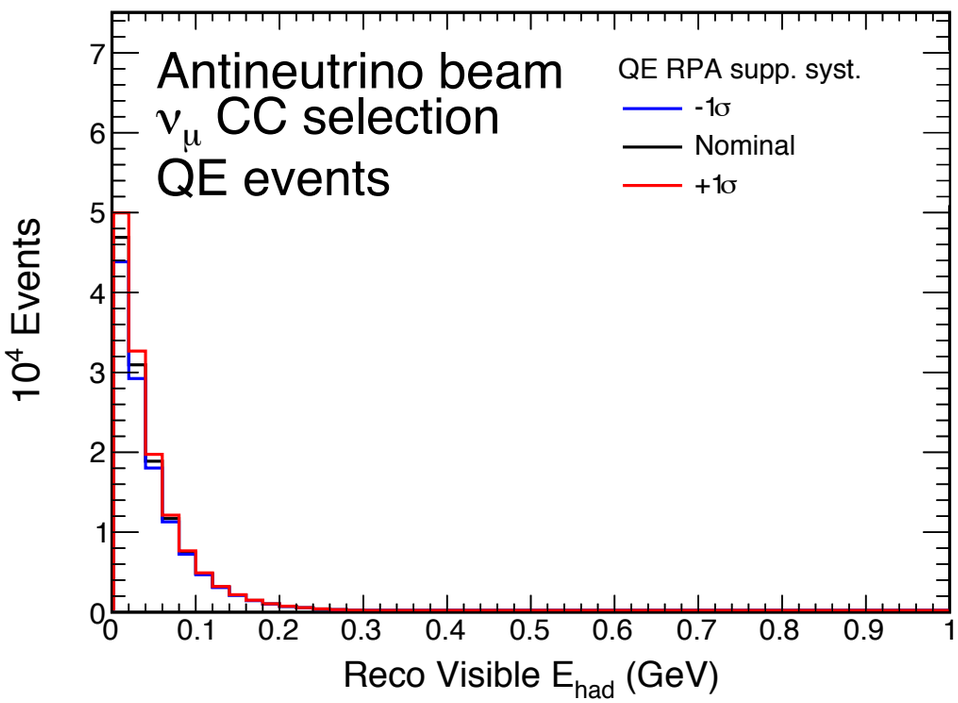
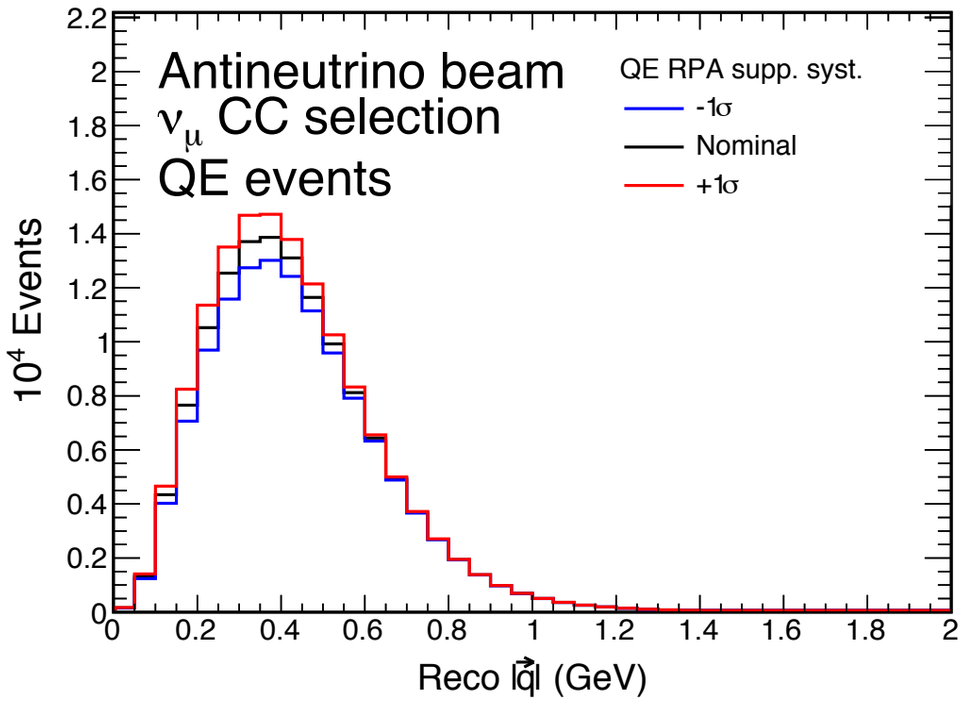
- A prong is a cluster of hits grouped into a single object. Prongs can give information on the topology of the event as the hadronic shower energy depositions can be reconstructed as multiple prongs.

RPA QE suppression systematic shift effect (neutrinos)









RPA QE suppression systematic shift effect (antineutrinos)