Recent NOvA GENIE tuning efforts

(used in NEUTRINO 2016 oscillation analyses)

on behalf of the NOvA collaboration

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Tufts University

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NuTune 2016 (Liverpool, UK)

Entering the generator tuning fray

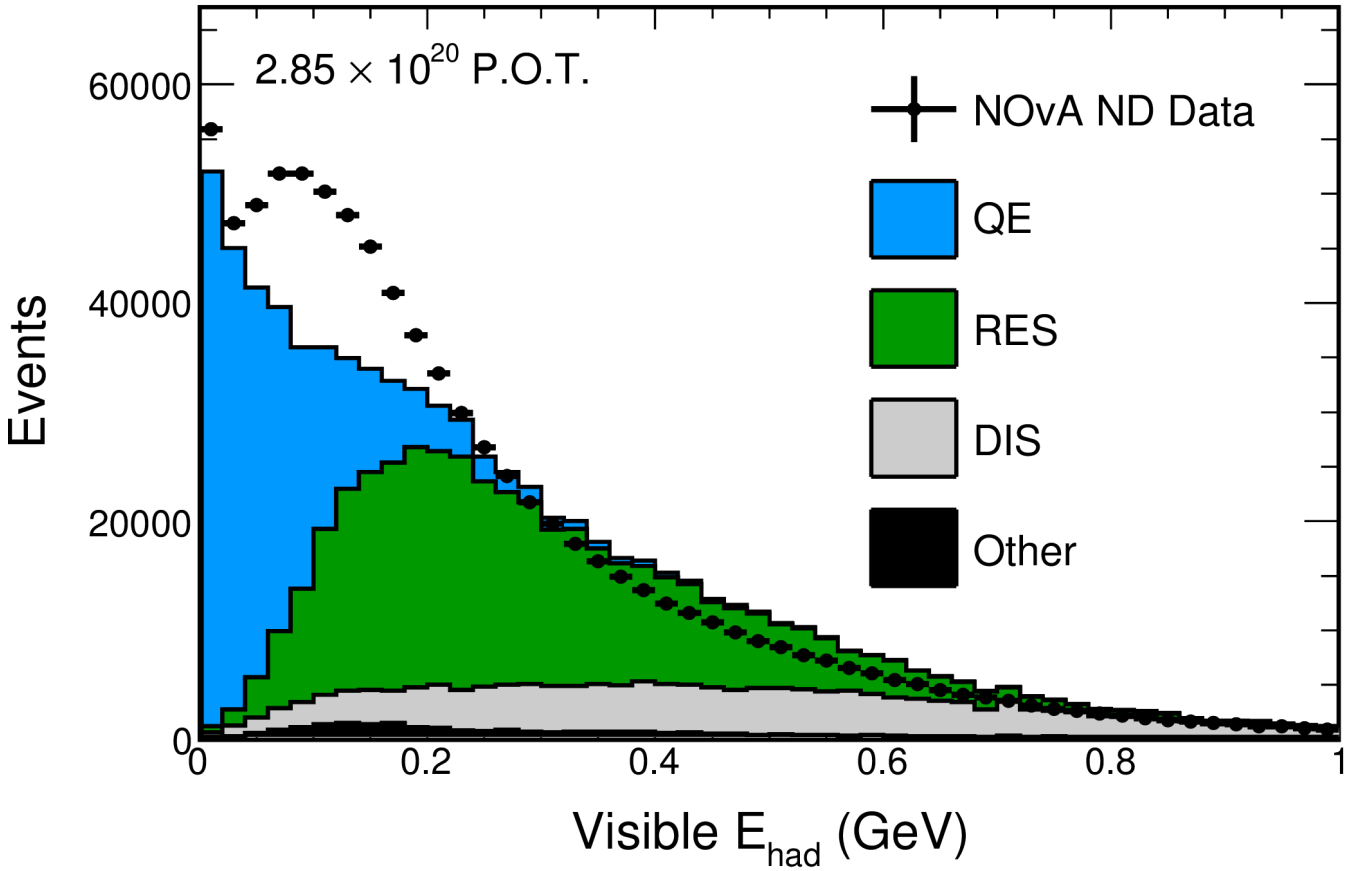
- Since start of running in late 2014, NOvA's near detector data has been flooding in
  - **~1M selected ν_μ CC events** (so far)
  - High-precision tests of cross section models now possible in regime with little previous data (E_ν ~ 2 GeV, carbon target)
- First results found default model (GENIE 2.10.4) and data disagree in some interesting ways

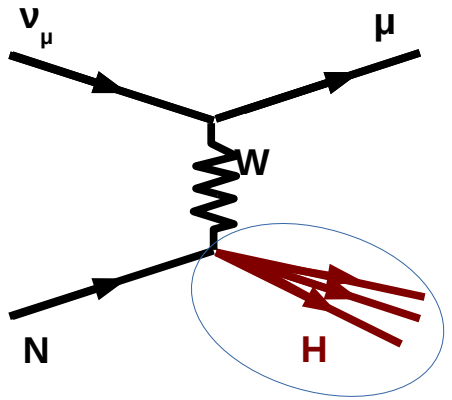
This talk:

<u>NOvA's first adventures in generator tuning</u>

The situation

NOvA Preliminary



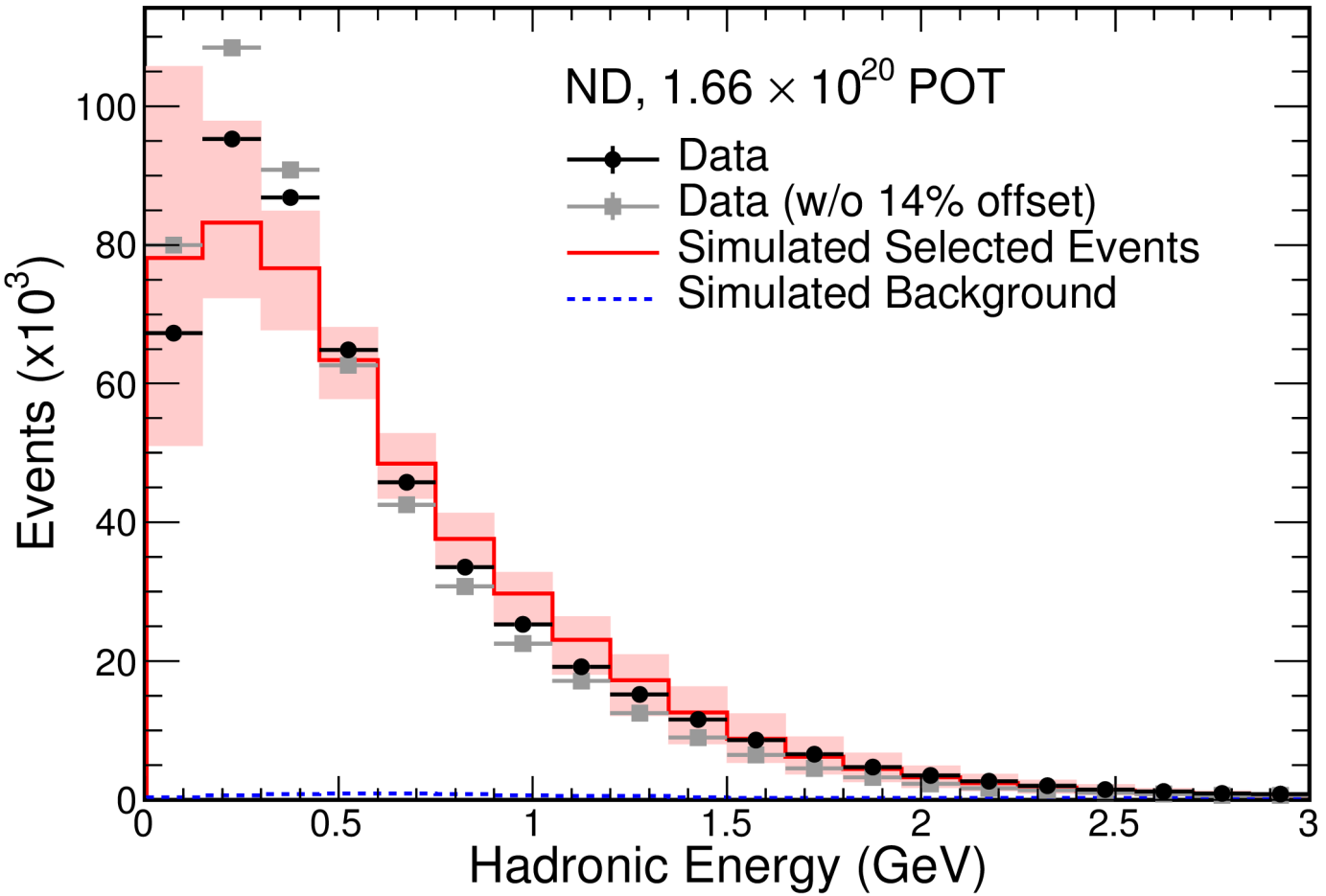


The energy in the hadronic recoil of CC ν_μ interactions is poorly modeled by GENIE 2.10.4.

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

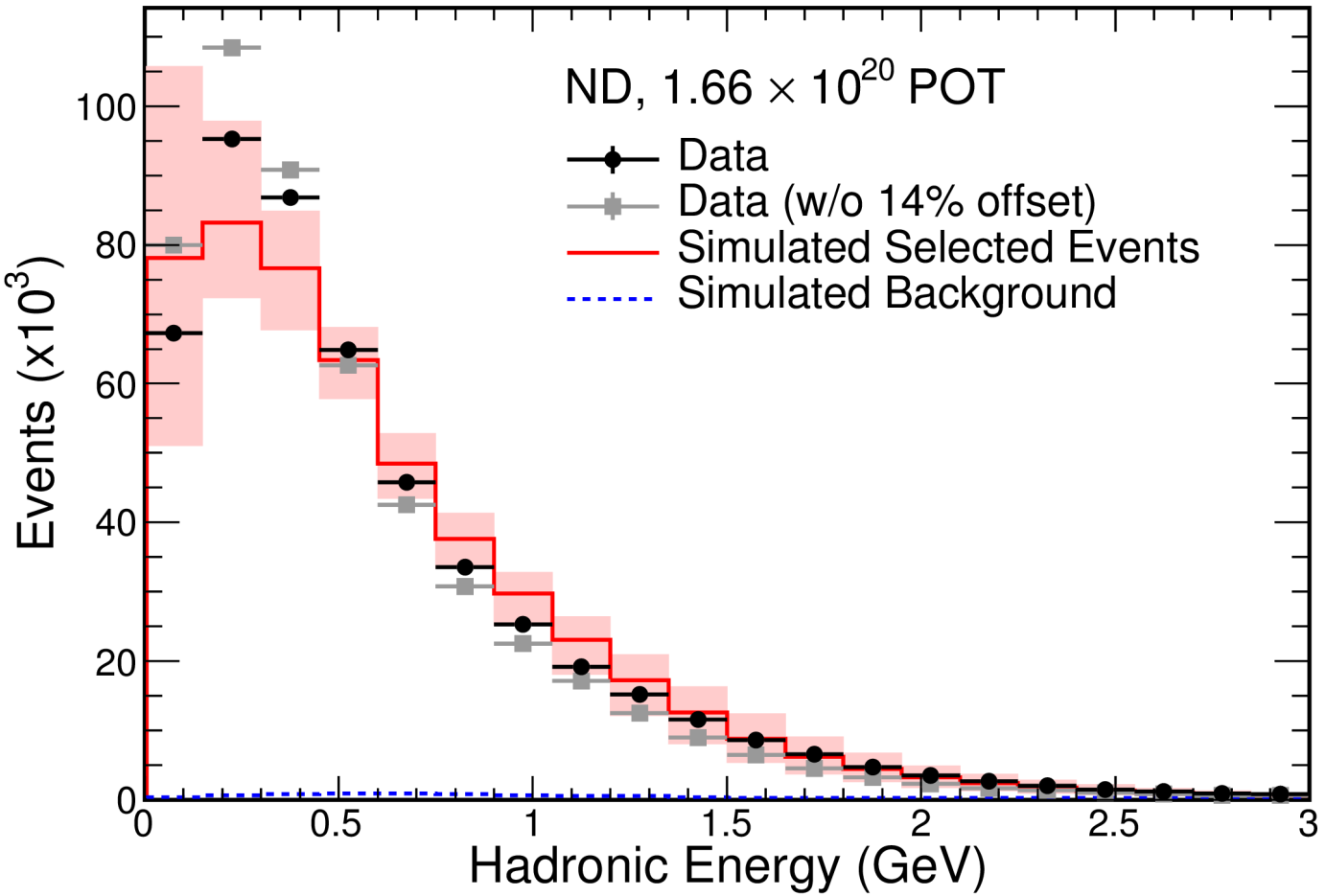
(so this directly affects oscillation inference)

First approach



In NOvA's first oscillation analyses (*Phys. Rev.* **D93**, 051104; *Phys. Rev. Lett.* **116**, 151806) the difference was treated as a calibration offset, with corresponding 100% uncertainty.

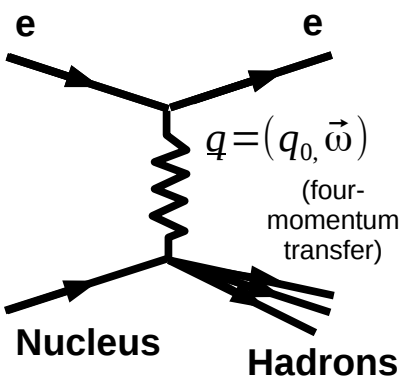
Dealing with disagreement

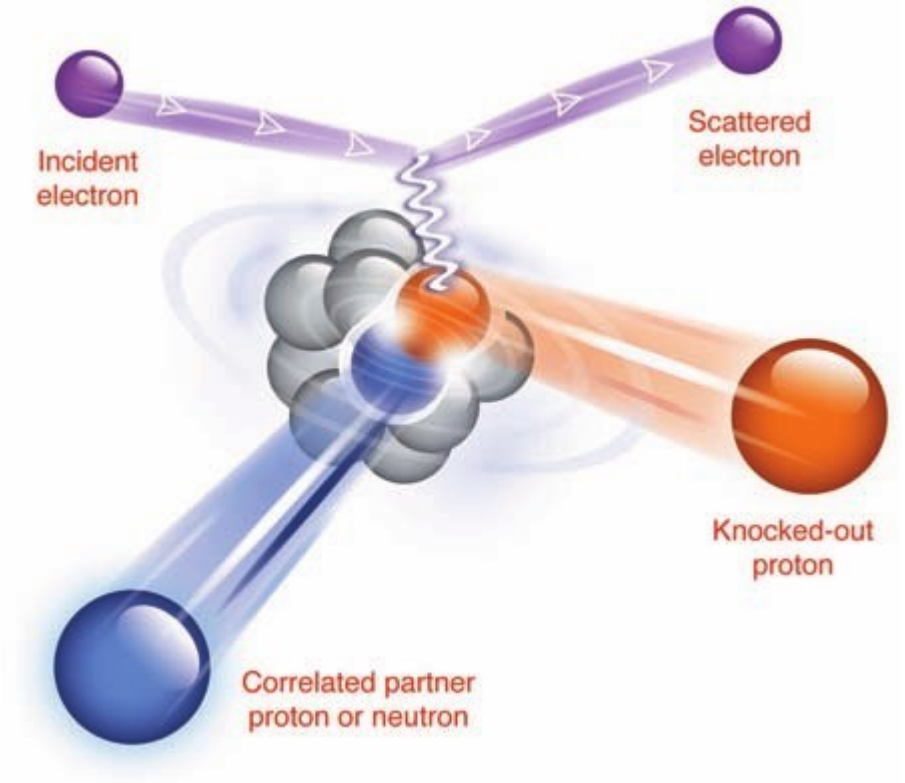


In NOvA's first oscillation analyses (*Phys. Rev.* **D93**, 051104; *Phys. Rev. Lett.* **116**, 151806) the difference was treated as a calibration offset, with corresponding 100% uncertainty.

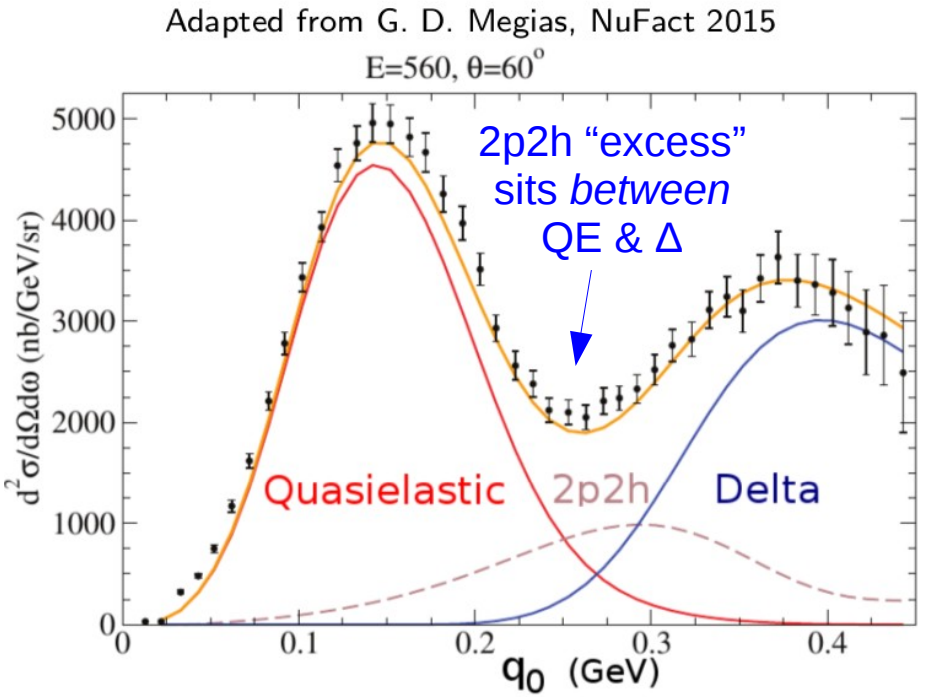
Second analysis approach:
Retune GENIE to ameliorate the disagreement.
Two ingredients...

Ingredient #1: 2p2h



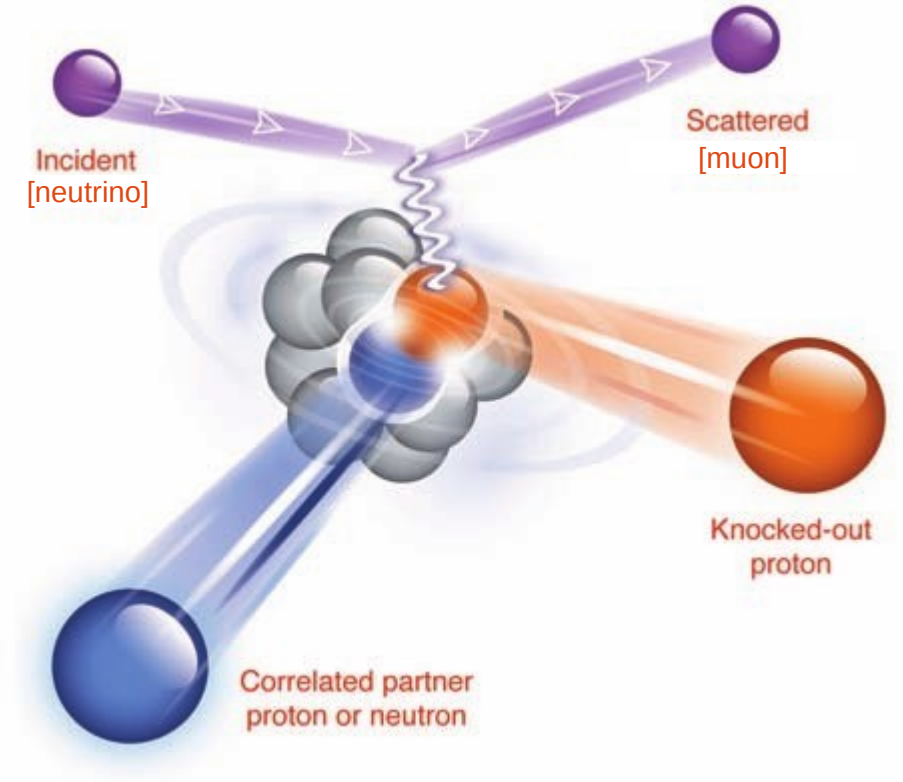


[adapted from R. Subedi et al., *Science* 320, 1476 (2008)]



Electron scattering

Ingredient #1: 2p2h



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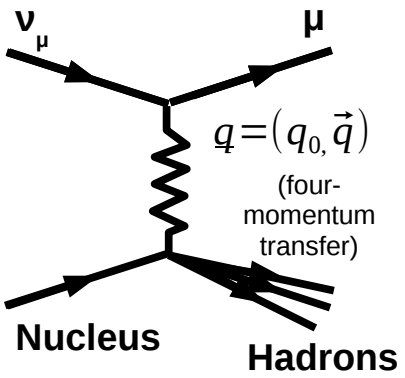
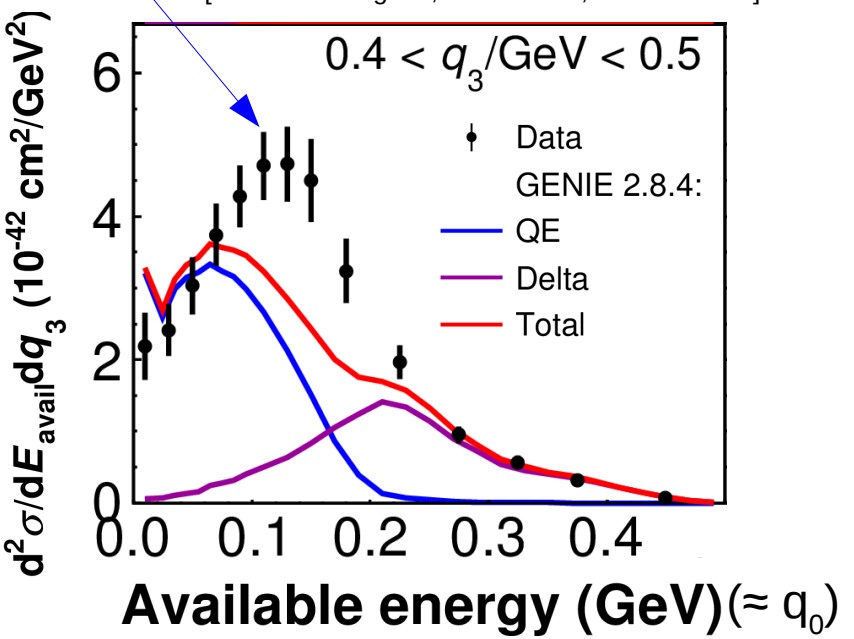


2p2h "excess" sits *between* QE & Δ

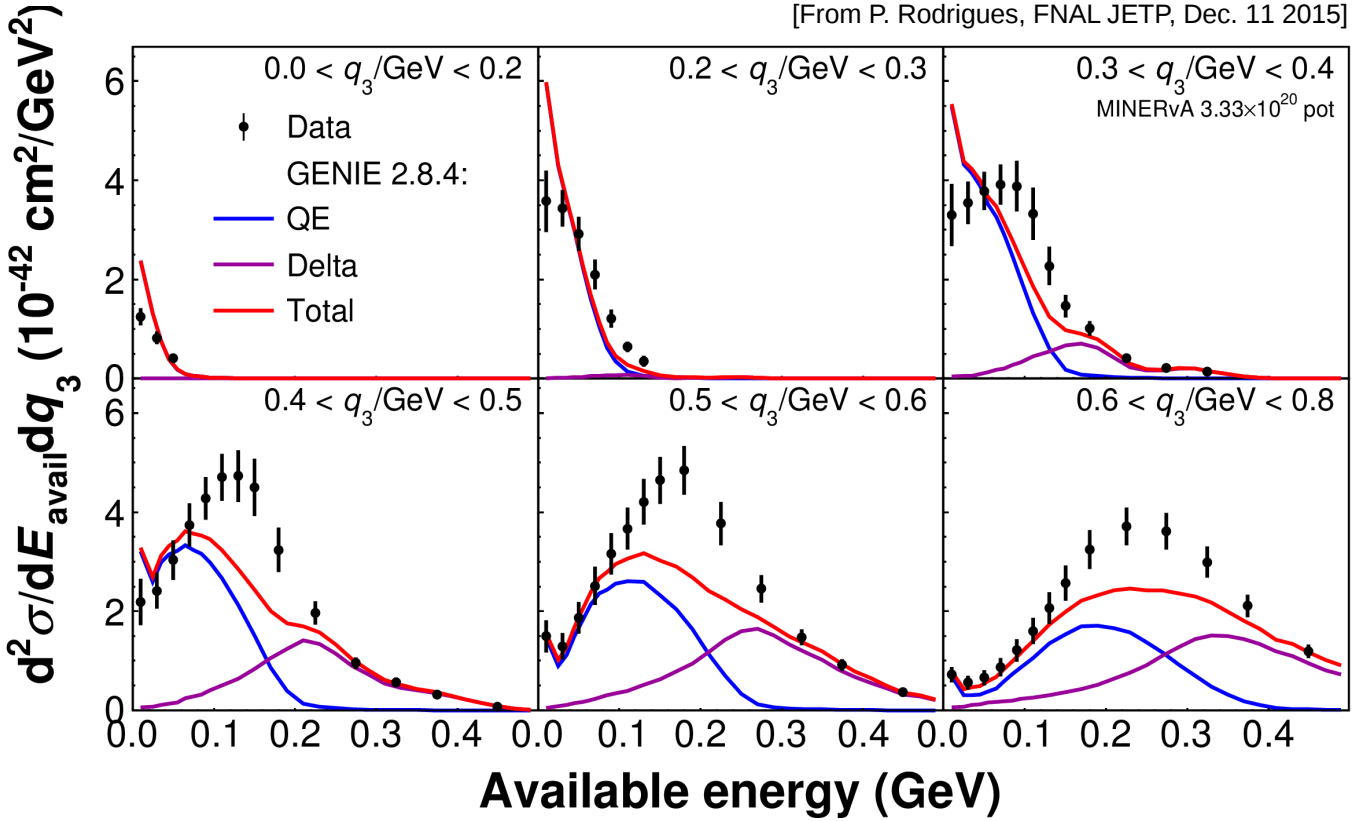
[From P. Rodrigues, FNAL JETP, Dec. 11 2015]

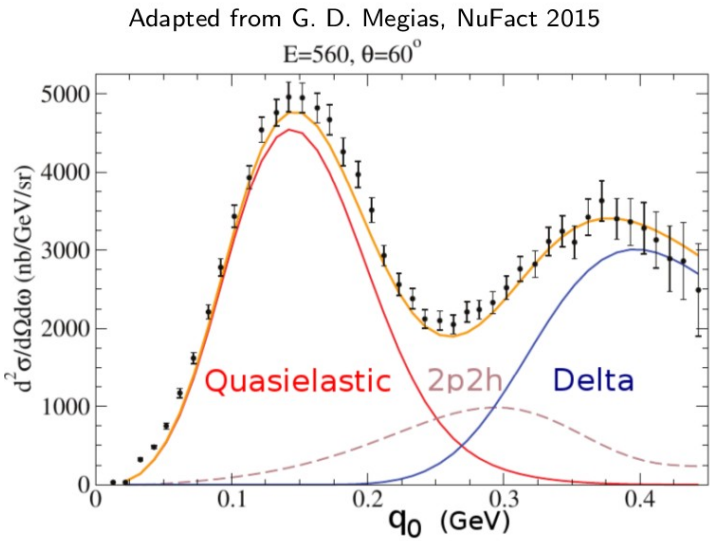


Neutrino scattering (MINERvA)

2p2h in the data: MINERvA

[From P. Rodrigues, FNAL JETP, Dec. 11 2015]



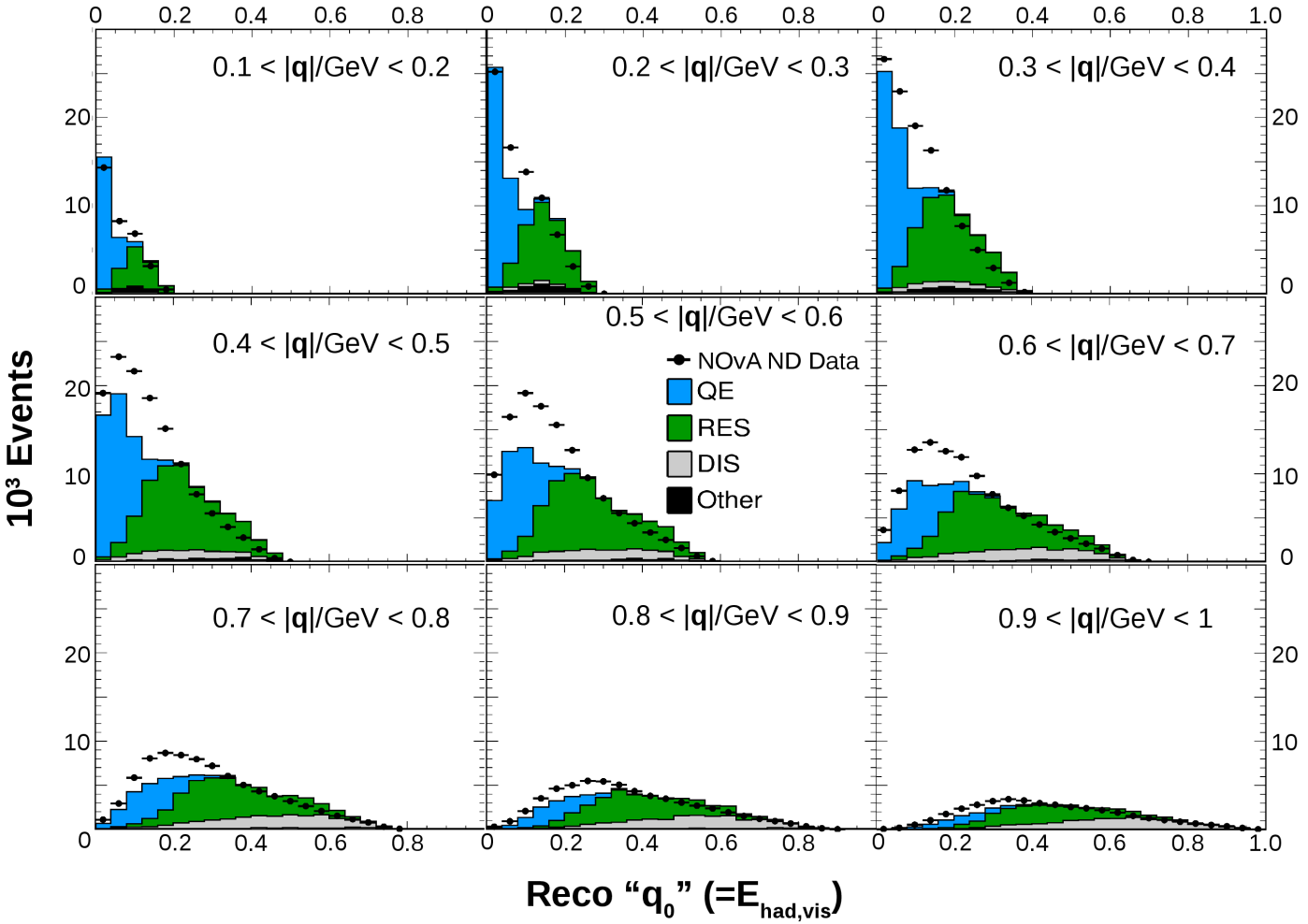


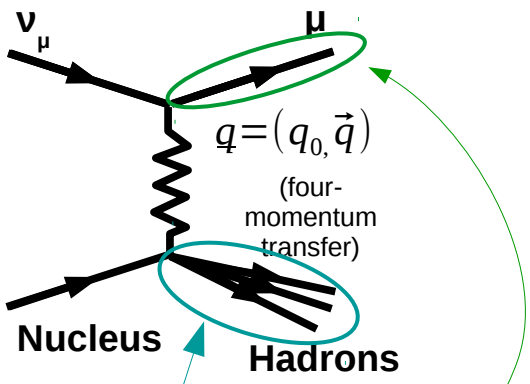
(Electron scattering, for comparison)

Story holds together across multiple slices in **|q|**...

2p2h in the data: NOvA

NOvA Preliminary





$q = (q_0, \vec{q})$

$q_0 = E_{had}$

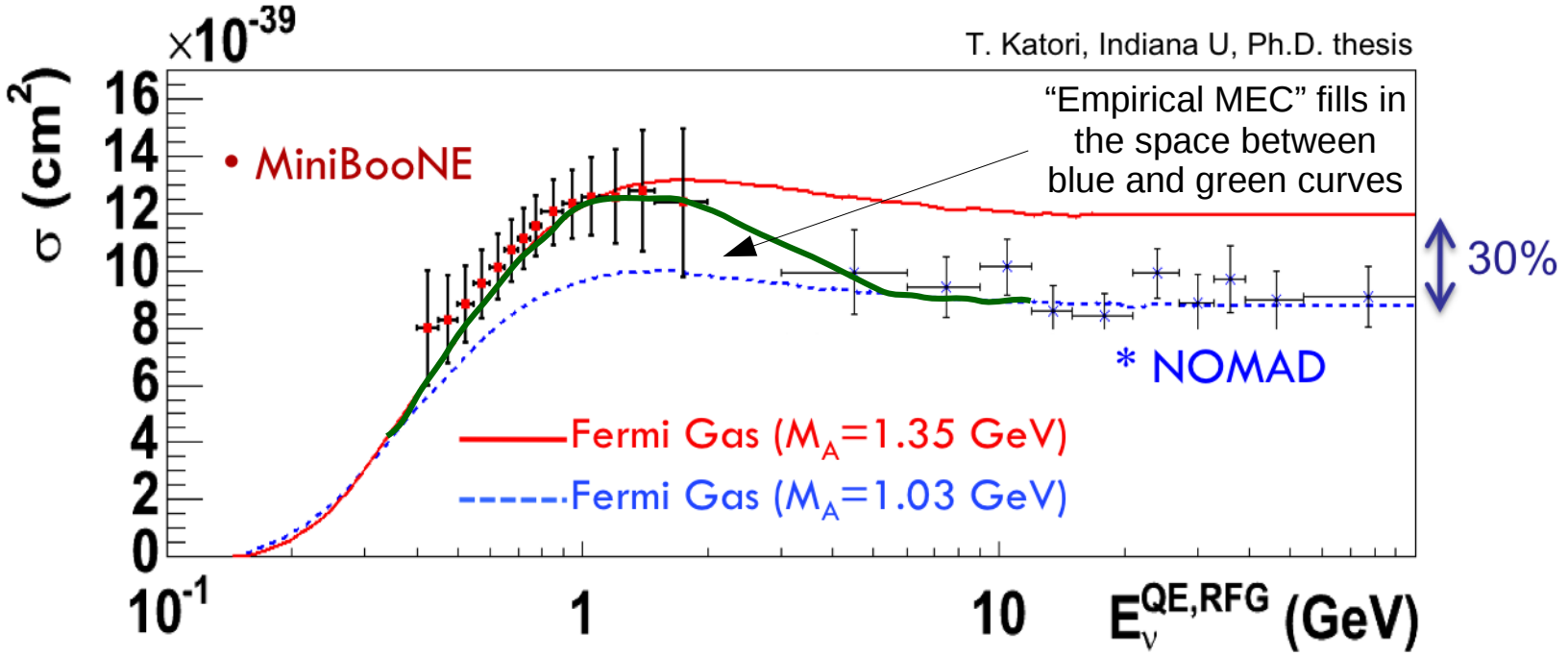
$E_\nu = E_\mu + E_{had}$

$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_\mu) - M_\mu^2)$

$|\vec{q}| = Q^2 + q_0$

… and shows up in the same way in NOvA ND data as well.

GENIE “empirical MEC”



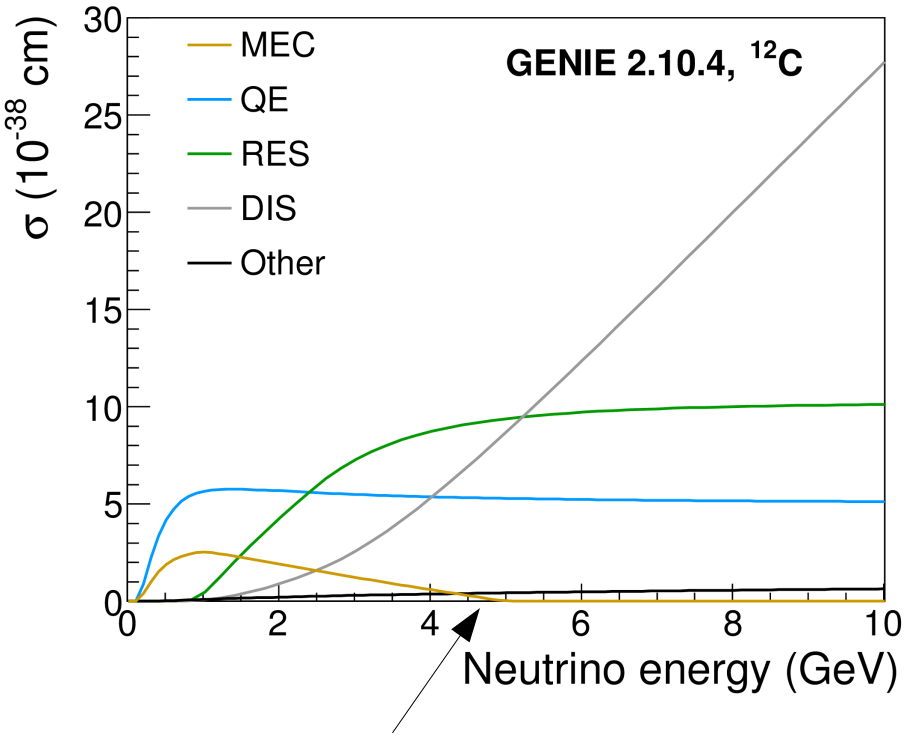
Since 2.6.0 (2010), **GENIE has an empirical model for 2p2h** based on reconciling MiniBooNE and NOMAD QE total cross sections.

Does this provide the missing piece of the cross section for NOvA?

Well... constructing it in this way leads to some unusual behavior...

GENIE “empirical MEC”

Problem #1:

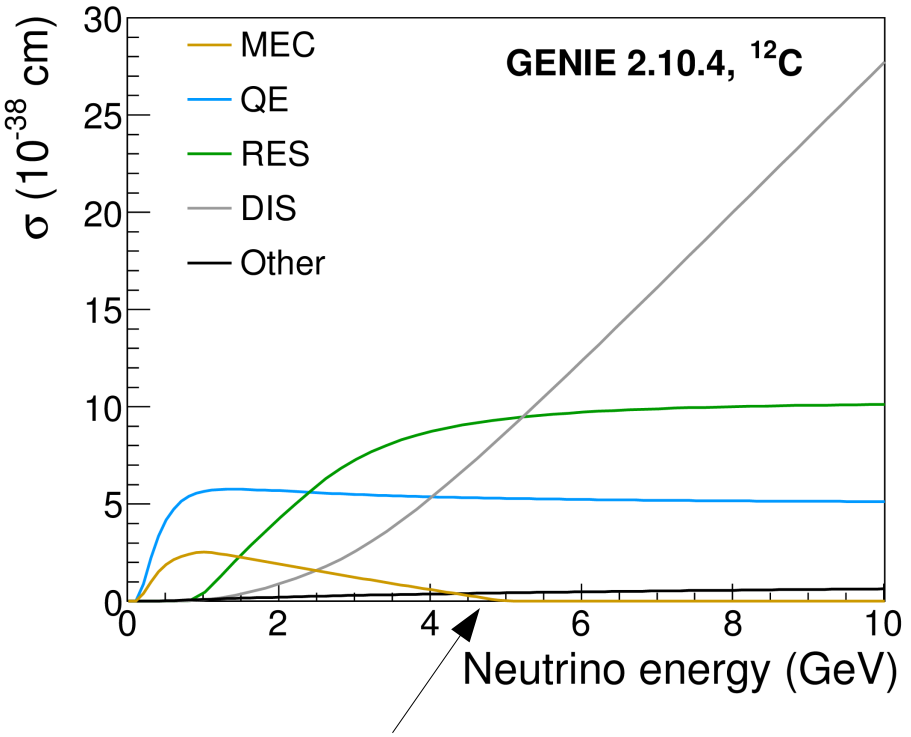


“Empirical MEC” **cross section forced to vanish** by E_ν = 5 GeV...

Newer MINERvA evidence (*Phys. Rev. Lett.* **116**, 071802) suggests otherwise:
2p2h effect same size for 5 < E_ν < 20 GeV as for E_ν < 5 GeV...

GENIE “empirical MEC”

Problem #1:



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Undo this via reweighting.

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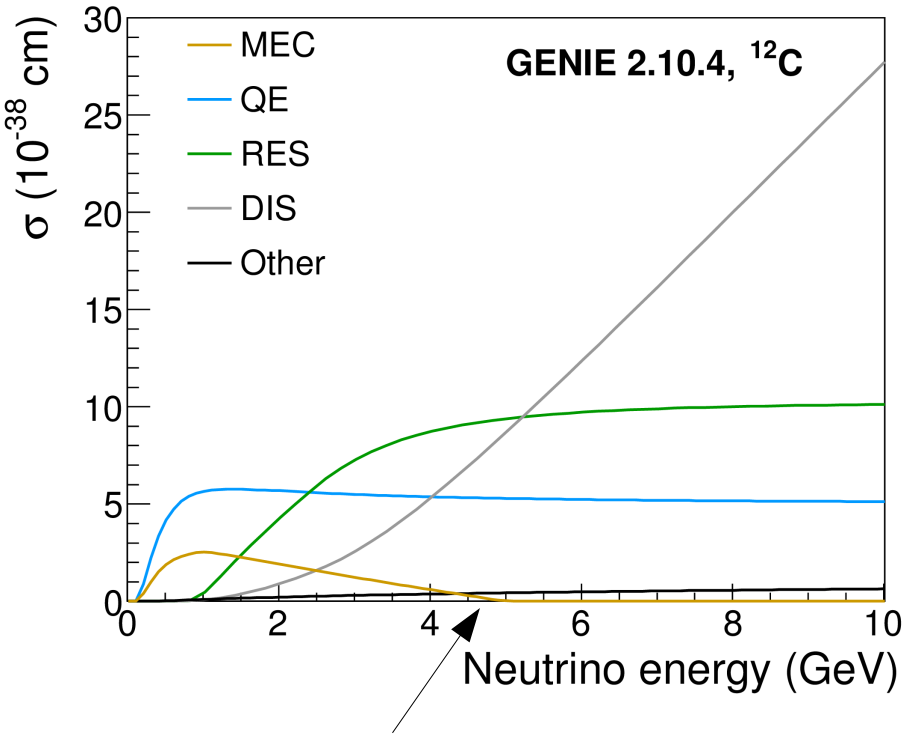

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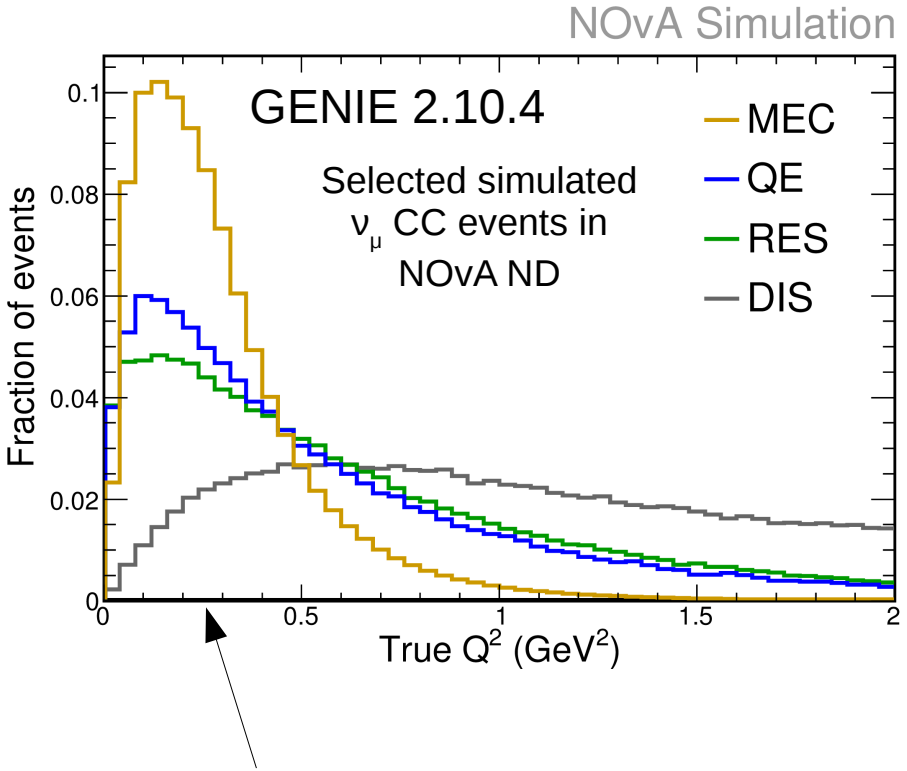

Momentum transfer behavior much softer for “empirical MEC” than other known processes...

GENIE “empirical MEC”

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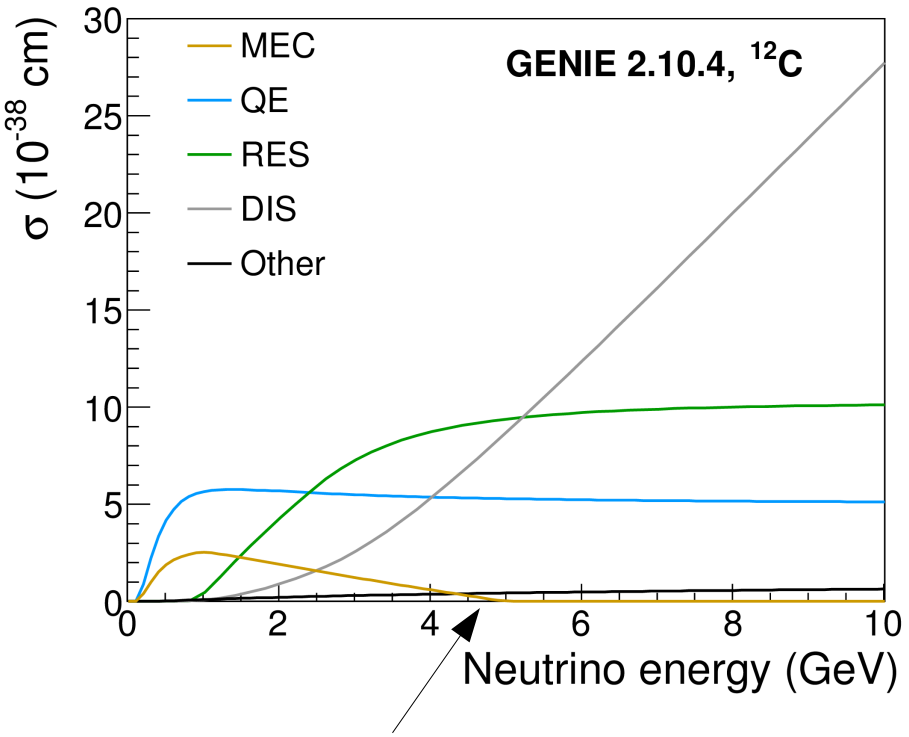

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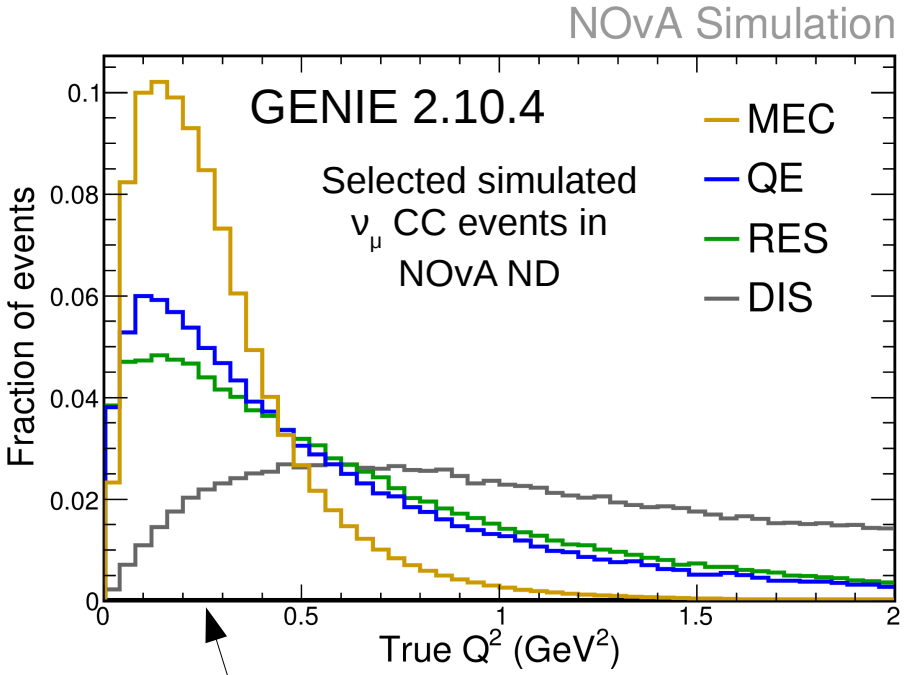
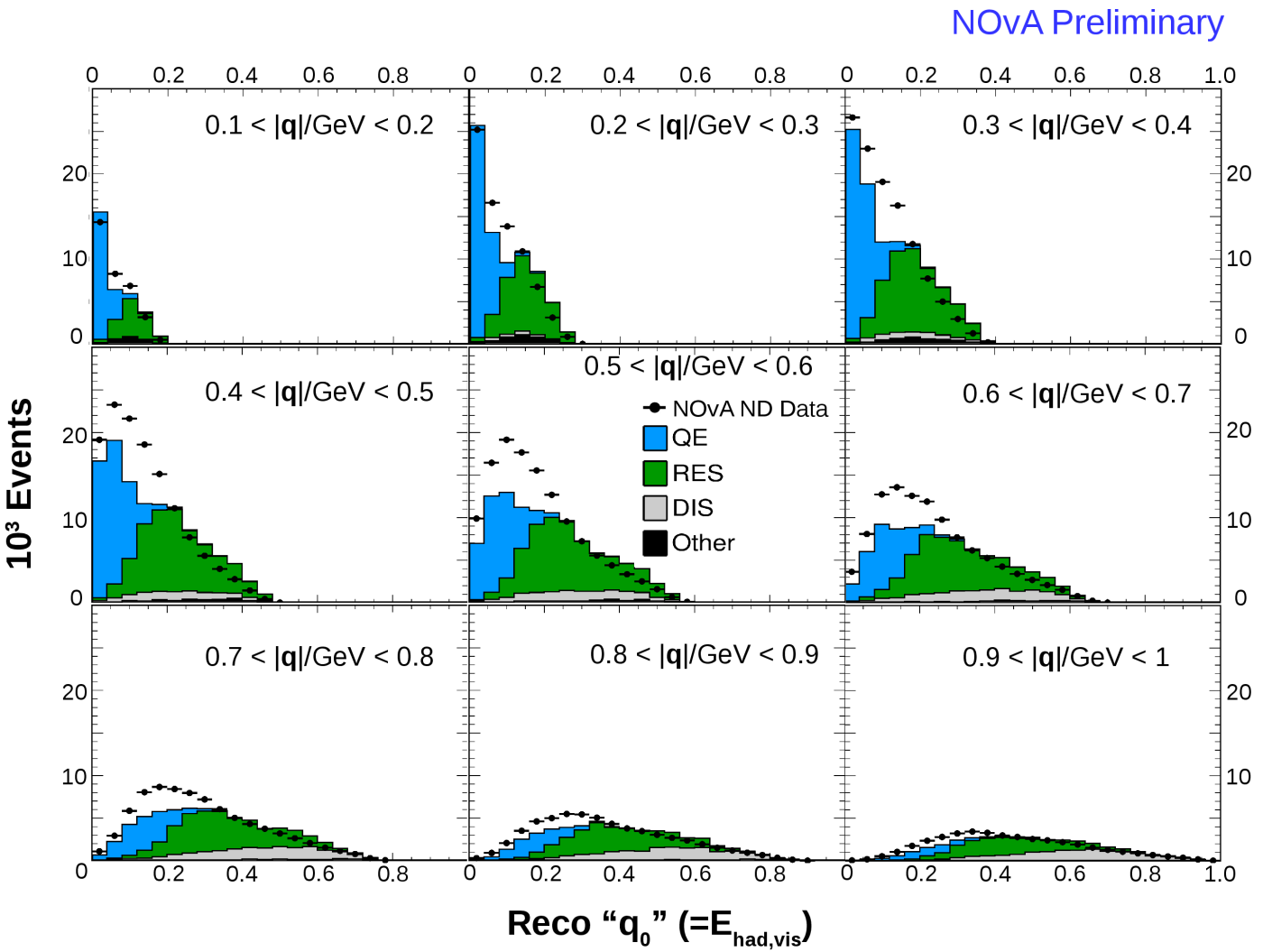
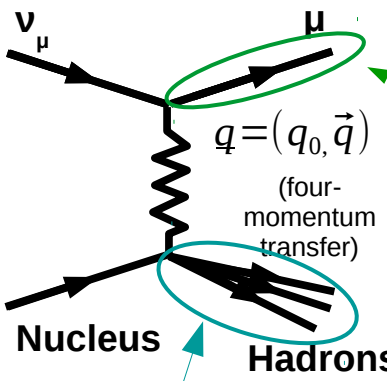


Momentum transfer behavior much softer for “empirical MEC” than other known processes...

Introduce different dependence based on NOvA data (next slides).

NOvA "empirical MEC"





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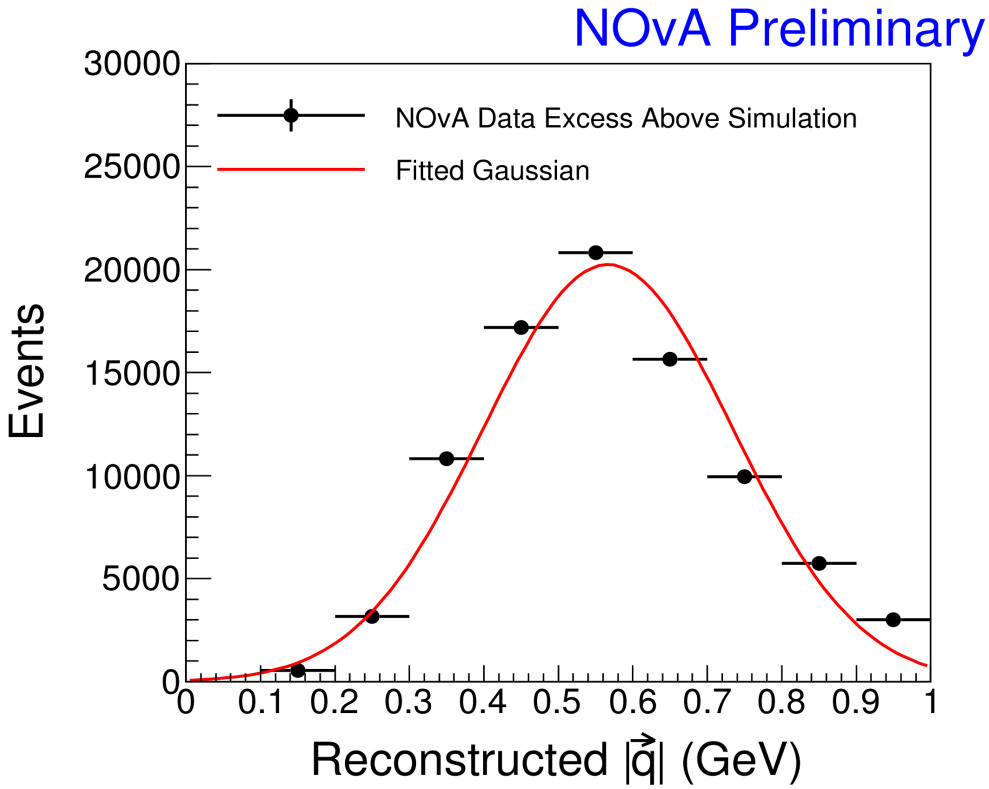
$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_\mu) - M_\mu^2)$

$|\vec{q}| = Q^2 + q_0$

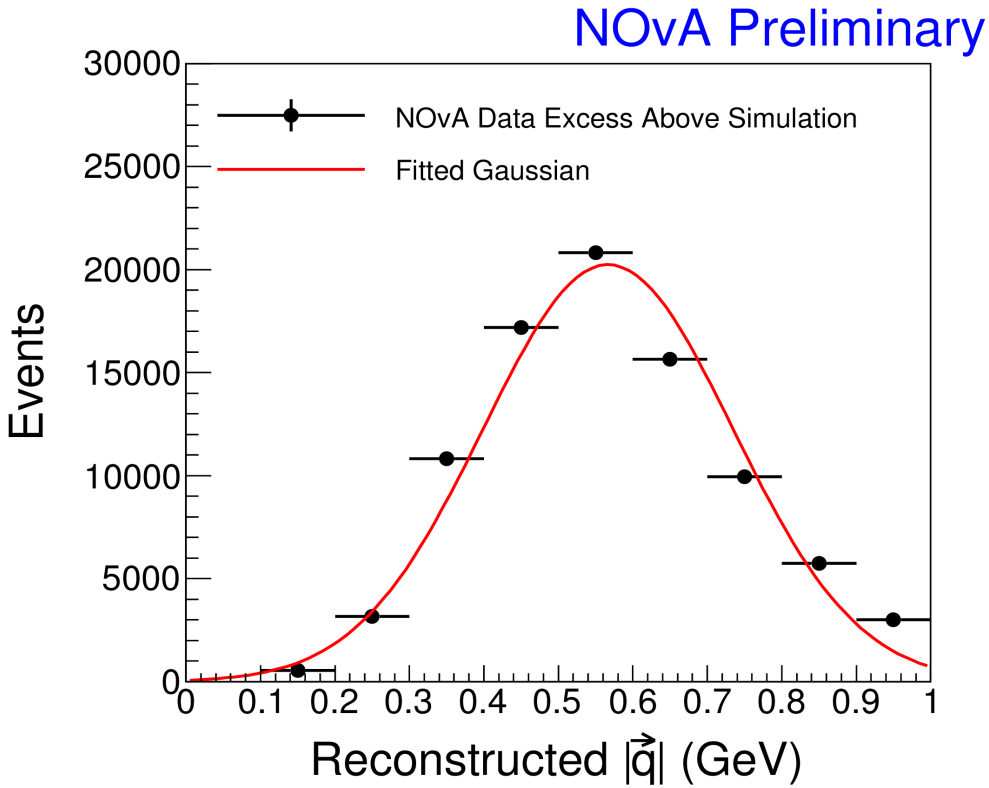
Take the integrated excess in each panel of this plot...

NOvA “empirical MEC”



… and fit it to a Gaussian ...

NOvA “empirical MEC”



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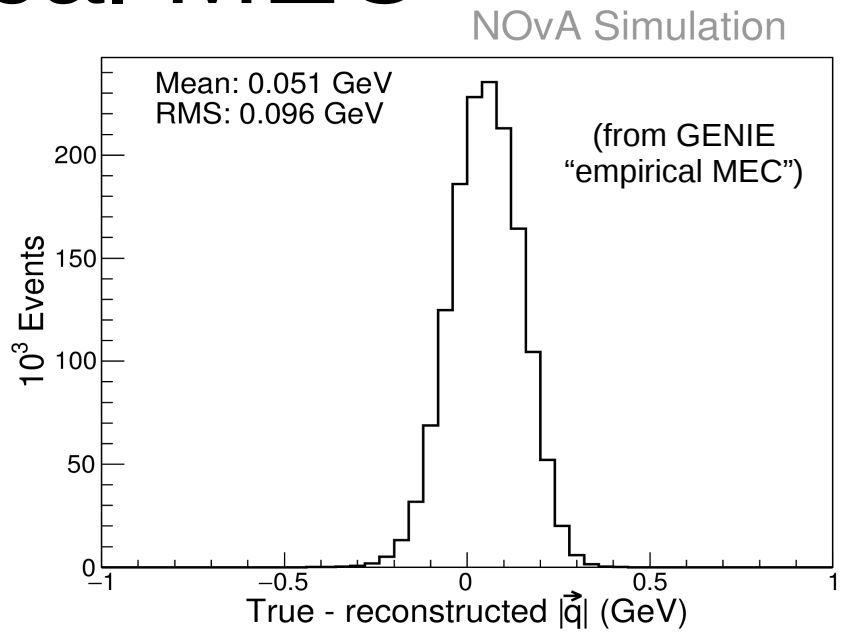
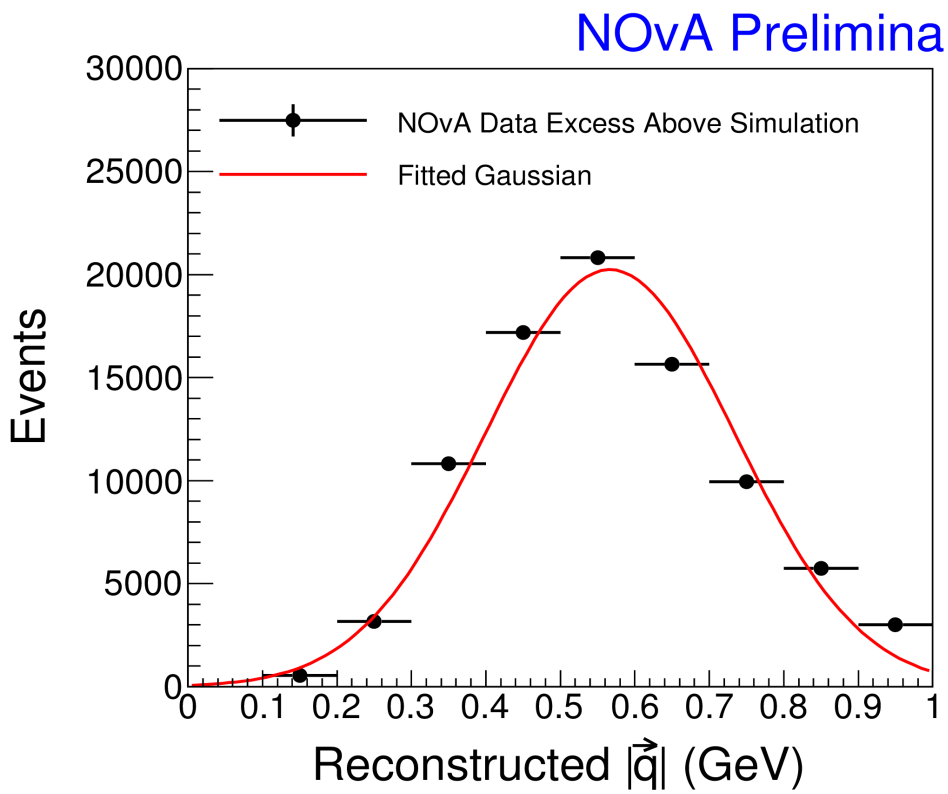


… then use model for detector response ...

NOvA “empirical MEC”



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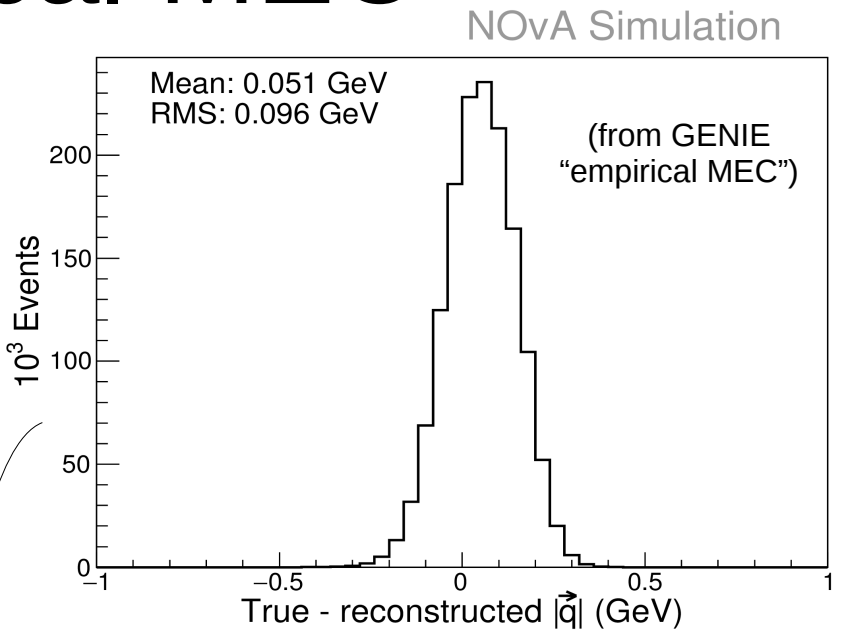

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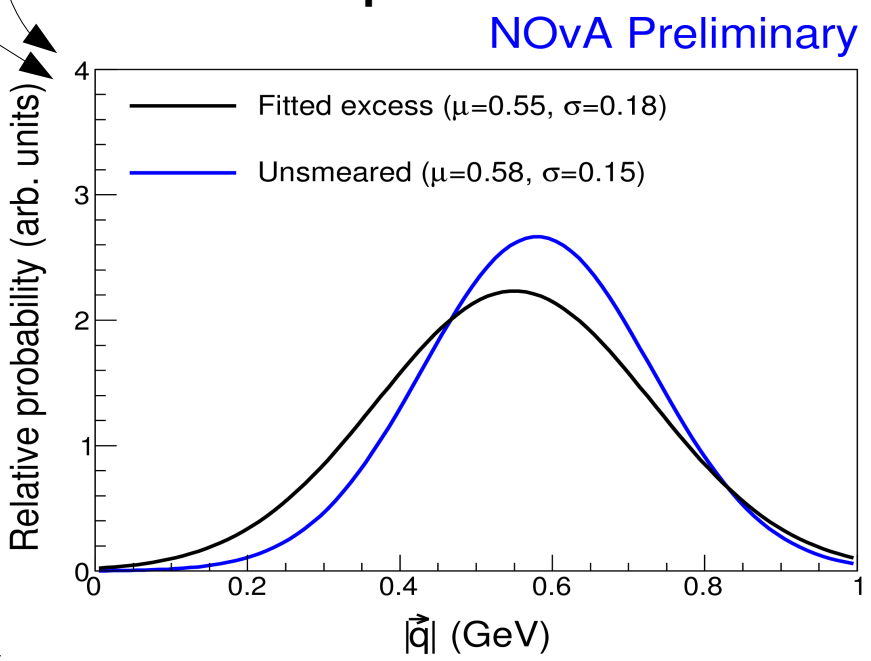


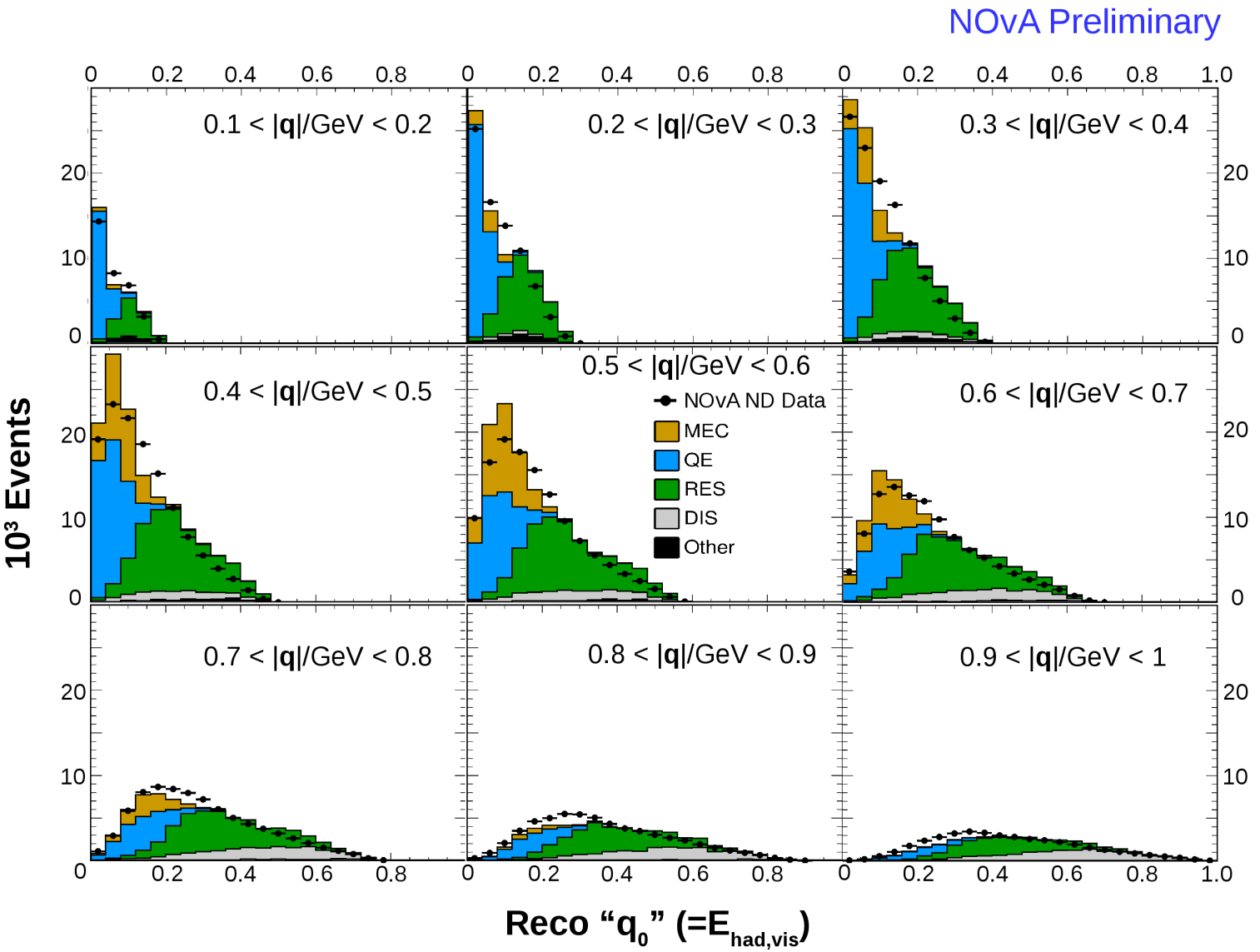
... to unsmear and yield the “true” |q| distribution of our excess.

Dilemma: what about q_0?

Need to assign correlations between q_0 and $|\mathbf{q}|$ to avoid GENIE "empirical MEC" choices that conflict with more recent data

- **Could (again) use our measured excess**... but:
  - Offers *little predictive power in regions we don't measure well* in ND (e.g., higher E_μ), so hard to trust extrapolation
  - Risks *doubly inheriting any other base model deficiencies* (since excess is computed relative to that)
- We choose instead to **use the (q_0,|q|) mapping from the GENIE QE model**
  - 2p2h interaction thought to (mostly) be alteration of QE
  - Definitely not *correct*, but well-defined, fully extrapolatable, and originating in a real model for a related process
  - Cover residual disagreement with data using uncertainties

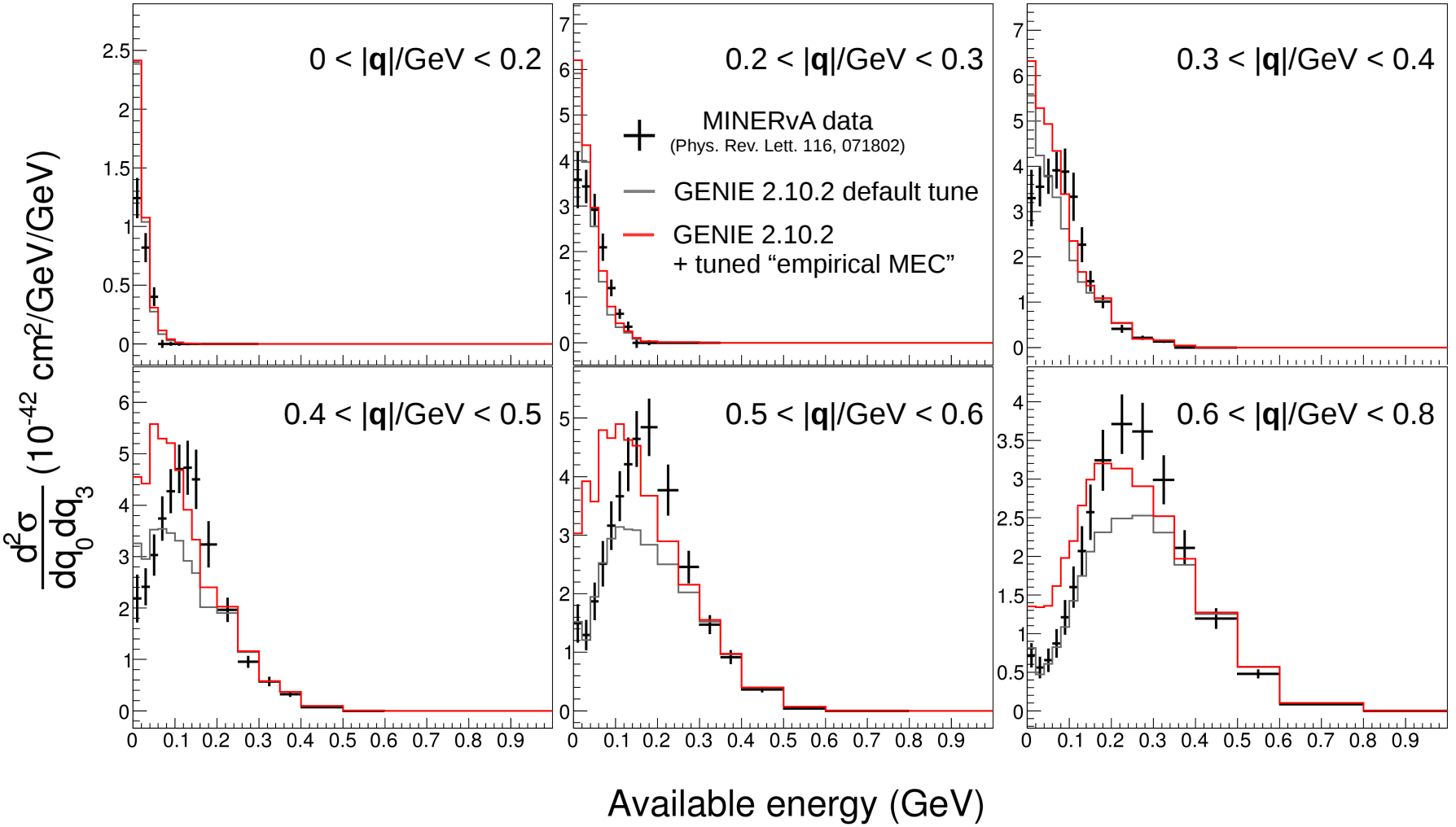
NOvA “empirical MEC”



While the q_0 behavior does not match the data excess very well (as expected!), **the NOvA tuned “empirical MEC” is a substantial improvement on the default tune**.

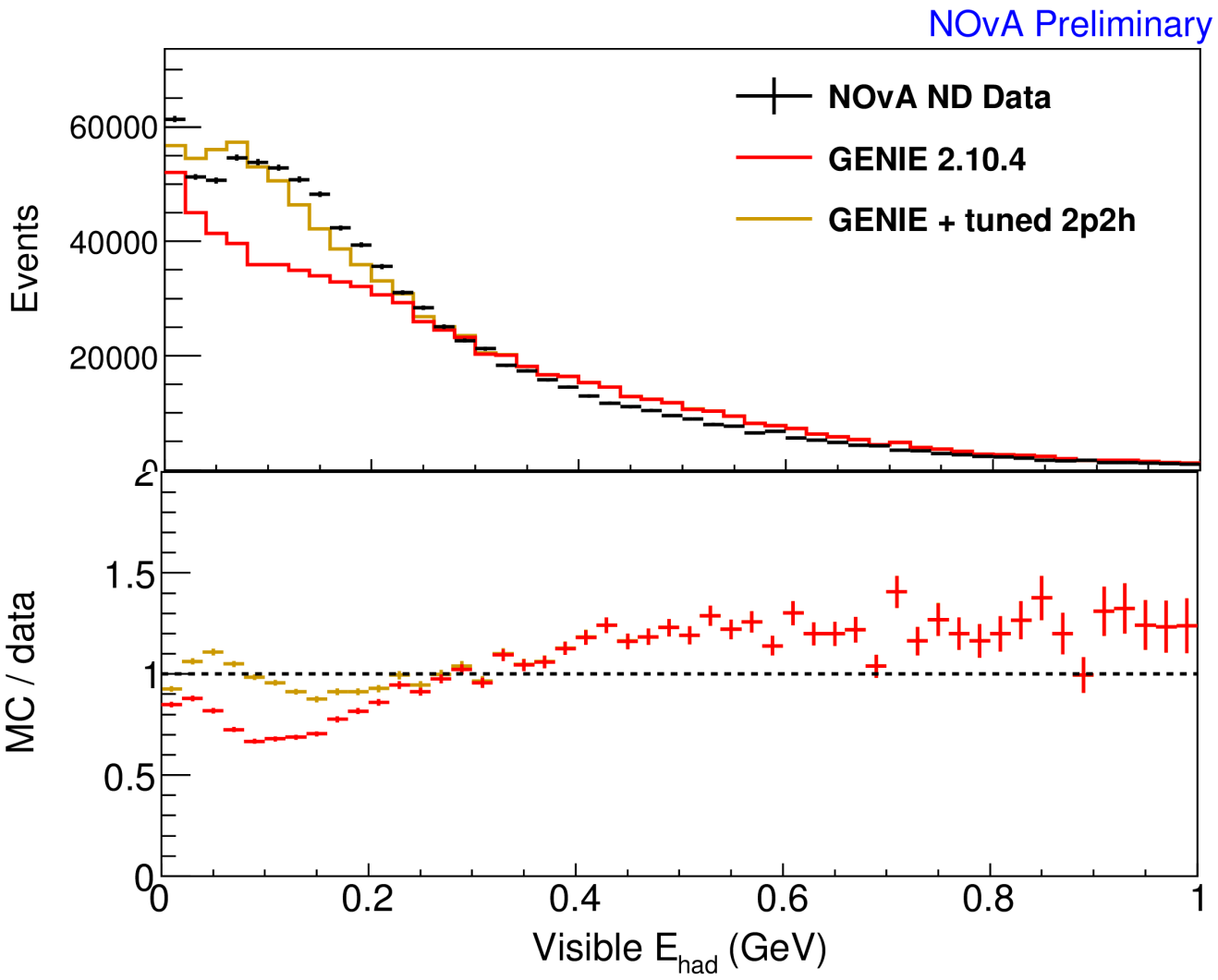
We apply a 50% uncertainty to the MEC component in oscillation analyses to cover the residual difference.

NOvA “empirical MEC”

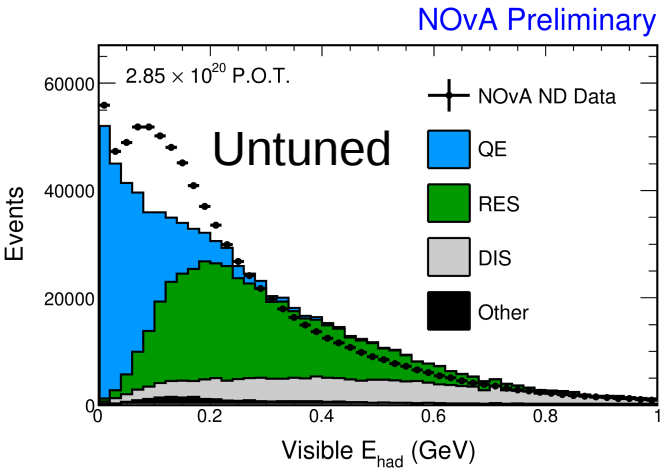


Comparisons to the published MINERvA data result in similar levels of agreement.

NOvA “empirical MEC”



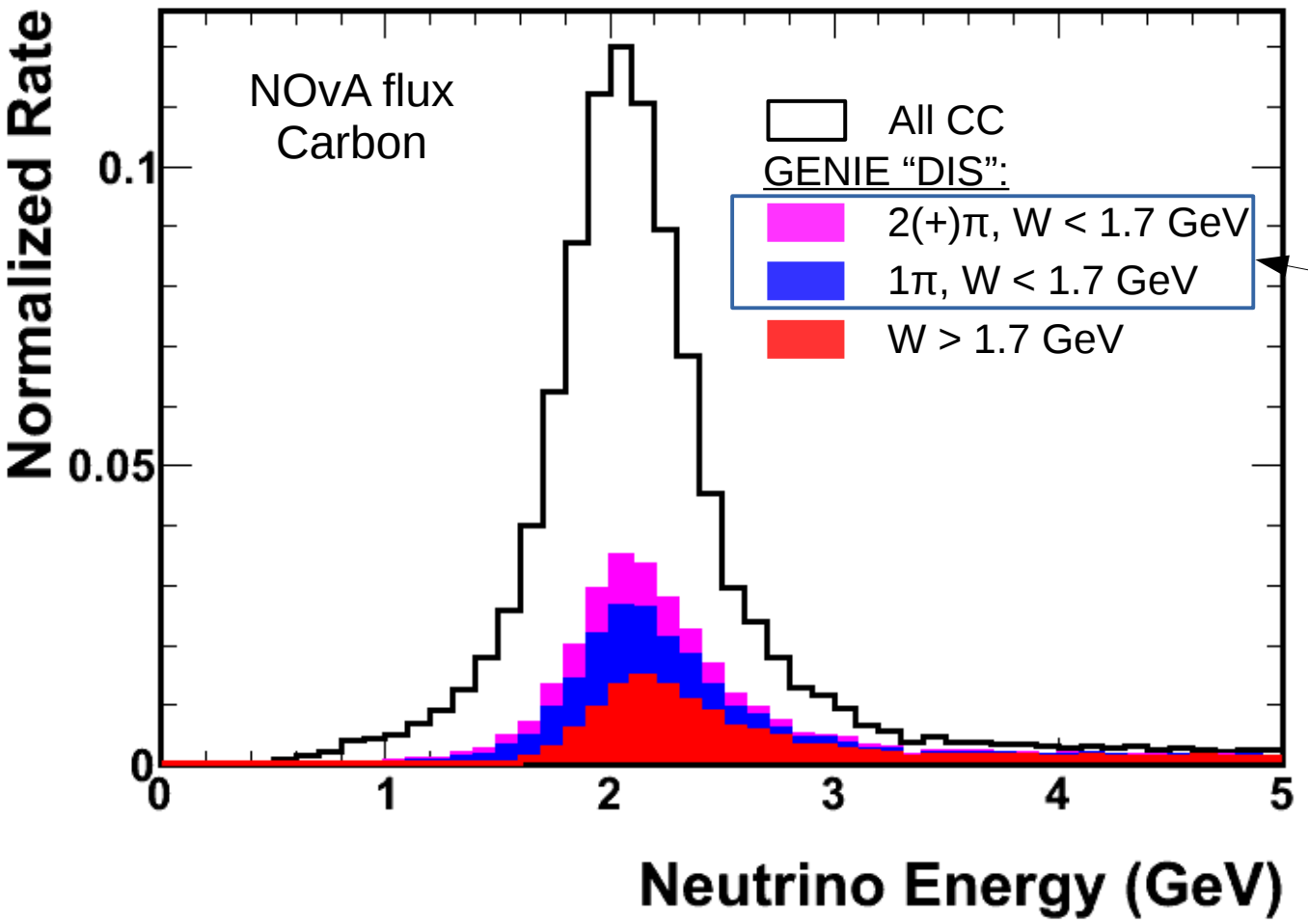
“NOvA empirical MEC” provides relief to the E_{had} tension not accessible by simply tuning the extant processes in the generator



Ingredient #1: 2p2h

- "Empirical MEC" from GENIE, tuned using NOvA ND data, improves prediction
- However: *we regard this tuning as only a stopgap*
  - Obviously, would like a full 2p2h model that agrees with data. (But we recognize that this is active work-in-progress by many theorists.)
  - In absence of that, **anticipate replacing the GENIE QE (q_0, $|q|$) mapping with one from a fully simulated, real 2p2h model** (like Valencia model coming soon) and revisiting tuning procedure
  - Need to investigate dependence of results on *nn-np* fraction

Ingredient #2: pion production



Nonresonant pion production is significant portion of NOvA CC event sample.

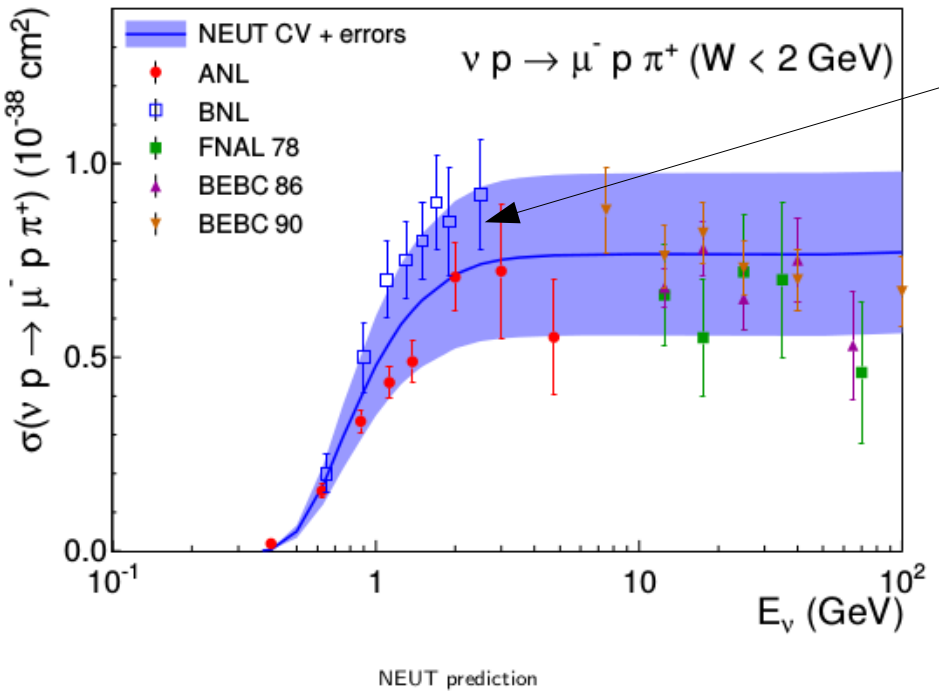
Note contribution of "continuum" production (resonance-dominated region, W<1.7 GeV).

Recent data reanalysis sheds some light on this subsample.

Ingredient #2: pion production

Reminder: Few-GeV single pion production on nucleons

- Production through resonances (chiefly Δ), plus a nonresonant component
  - Nonresonant is part of the Rein-Sehgal model in NEUT, part of DIS in GENIE
- Three CC channels and four NC channels. Data on NC is very limited
  $\nu_\mu p \to \mu^- p\pi^+$, $\nu_\mu n \to \mu^- p\pi^0$, $\nu_\mu n \to \mu^- n\pi^+$
- The only data around $E_\nu = 1$ GeV is from ANL and BNL bubble chambers



[slide from P. Rodrigues]

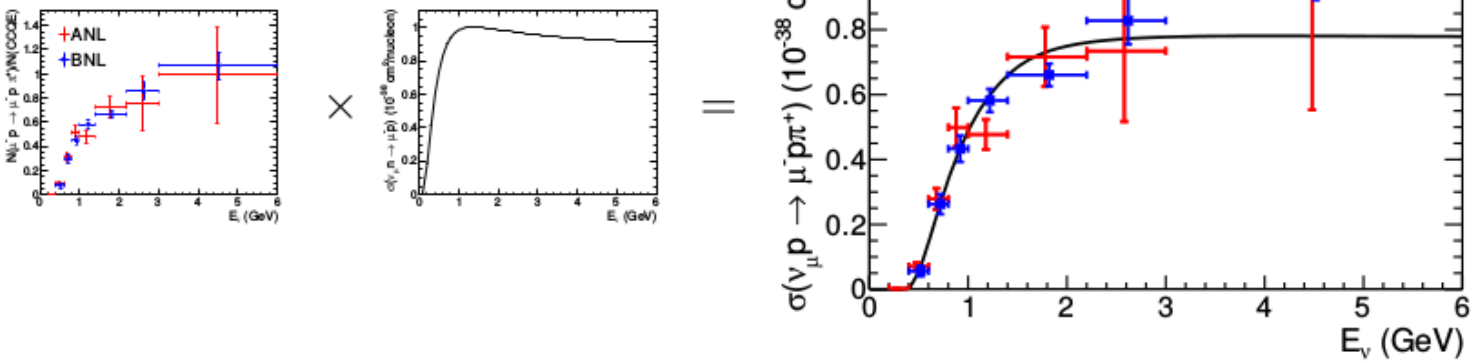
Nucleon-level cross sections are constrained by deuterium data.

Two world datasets at single-GeV energies disagree by 50%.

Result: **large uncertainties on single pion production in generators** (50% uncertainty on non-resonant contribution in GENIE).

Puzzle resolved

Consistentifying the ANL and BNL data, all *W*



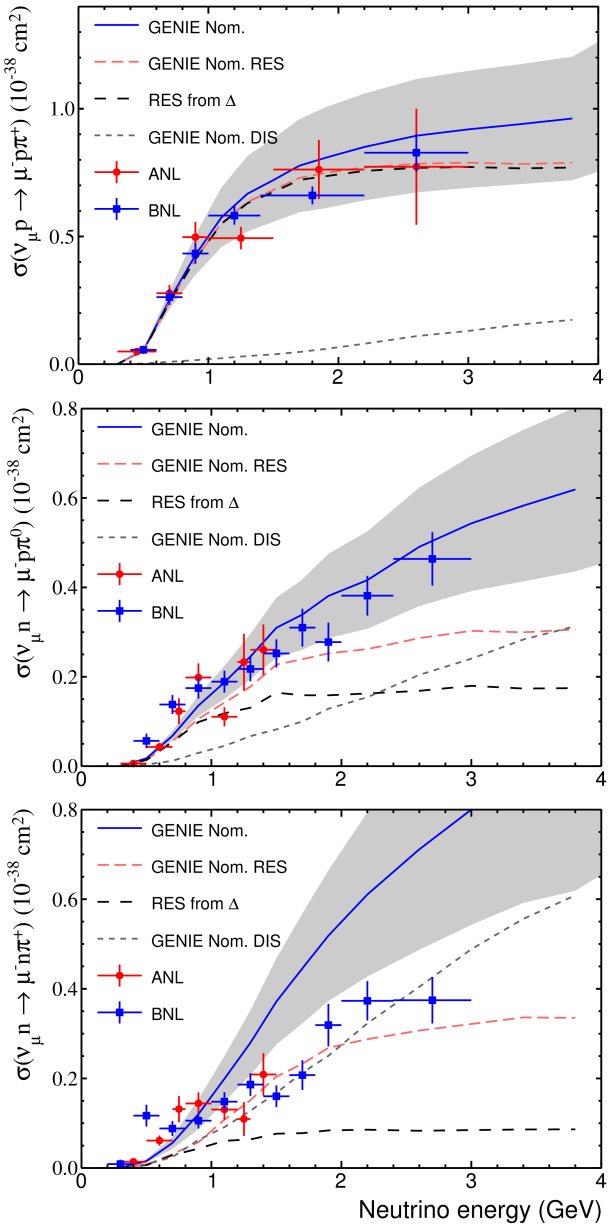
- Assume the difference is from some overall normalization factor, like flux, take the single-pion/CCQE ratio, then multiply by the well-known CCQE cross section to get single-pion xsec
- Shown for $\nu_\mu p \to \mu^- p\pi^+$. Can do the same for the other two channels

[slide from P. Rodrigues]

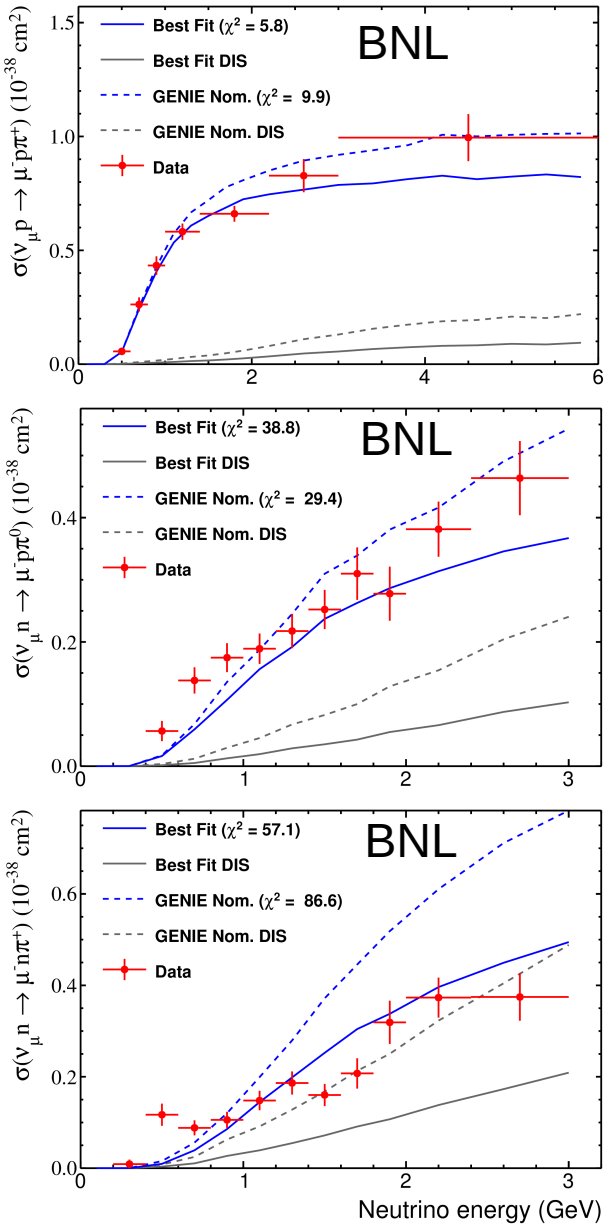
Since both experiments published both CCQE & single pion measurements, can use the ratio of them, compared to well known CCQE cross section, to work out normalization.

Turns out **they agree after all, after the correction**. [*PRD* **90**, 112017]

Adjust GENIE prediction

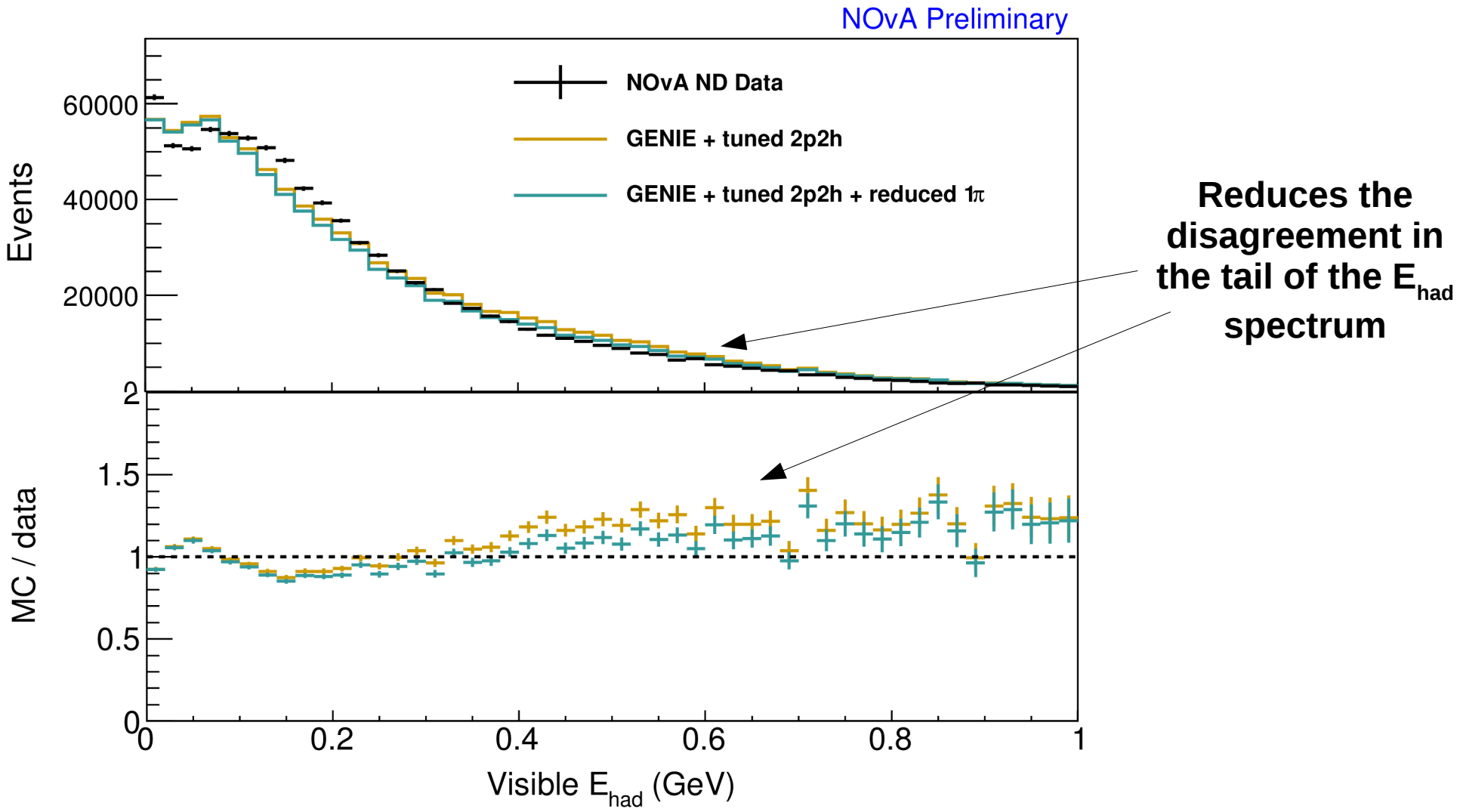


Best fit of components results in **reduction of normalization of nonresonant "continuum" single pion production by ~50%**



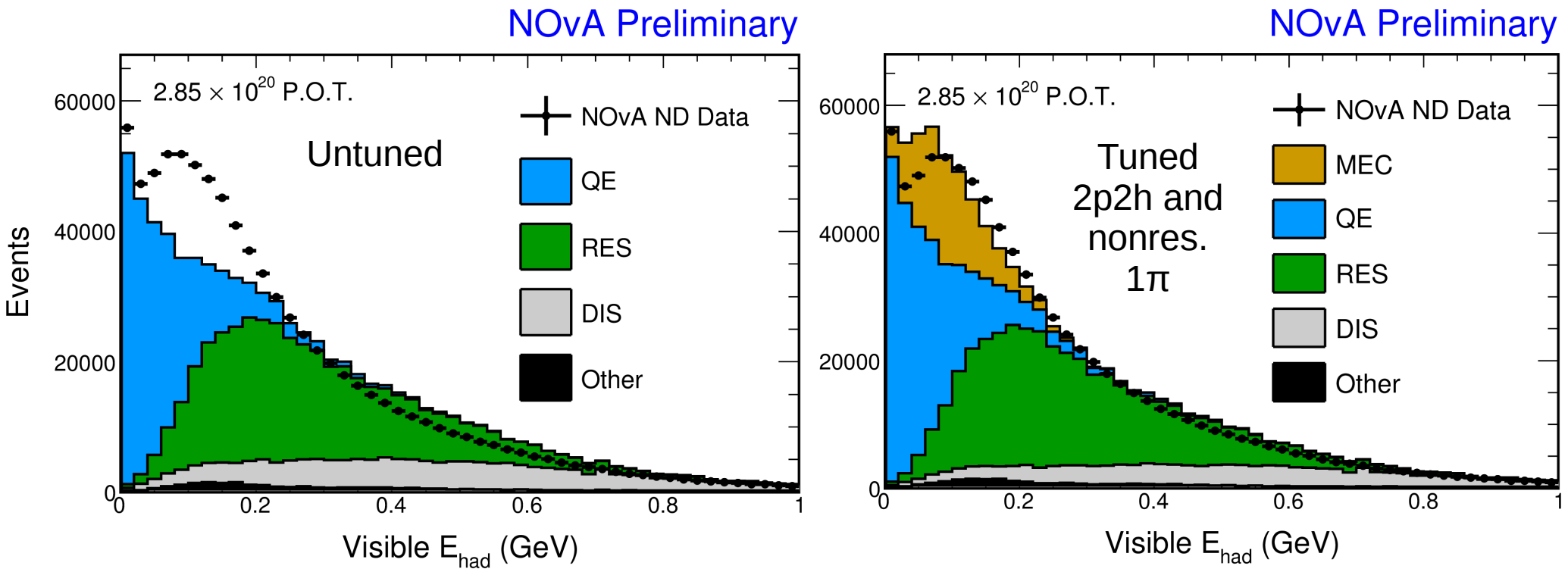
[arXiv:1601.01888]

Effect on NOvA ND spectrum



Reduces the disagreement in the tail of the E_{had} spectrum

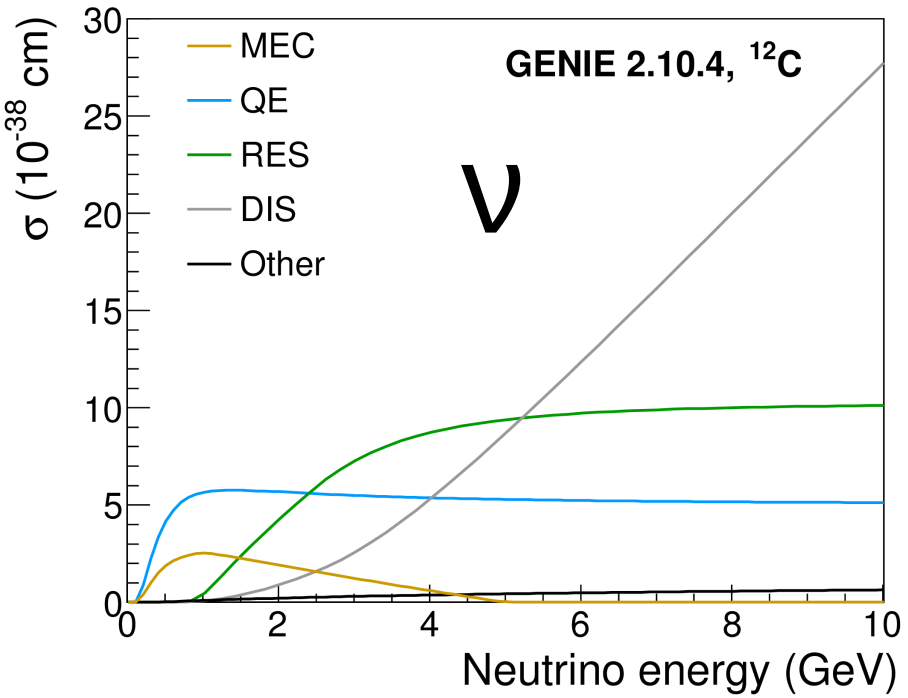
Tuning results

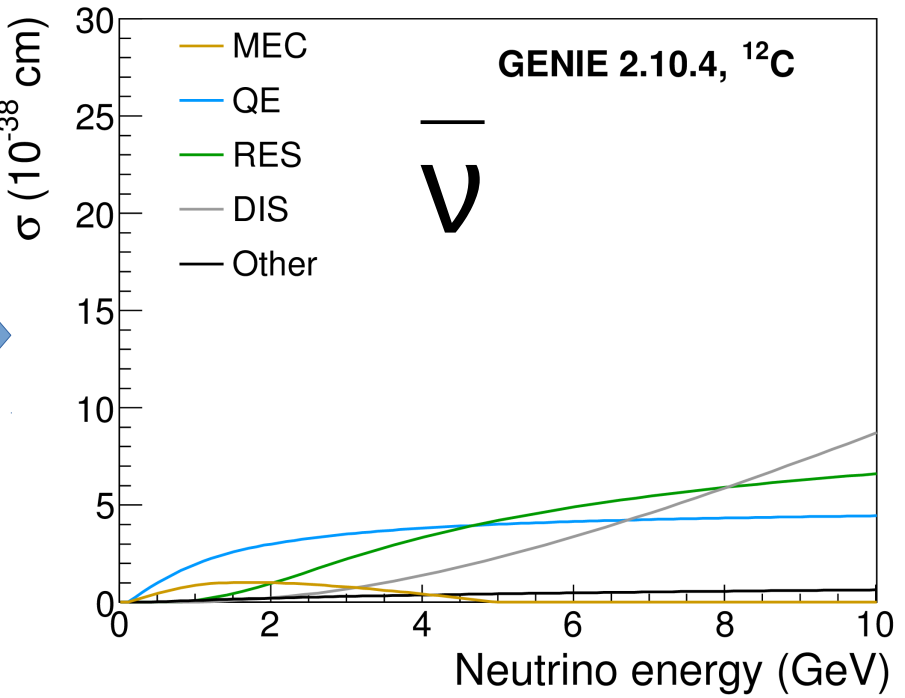


We were able to significantly improve the GENIE prediction for our ND ν_μ CC hadronic recoil distribution by using GENIE's “empirical MEC” model, tuned to our ND data, and by reducing the nonresonant single pion production component of DIS by 50%.

(As noted earlier, however, we don't consider this a *final* tuning by any account.)

Open questions:
Does the story hold up for $\bar{\nu}$?





We expect to see 2p2h at a similar fraction of the QE rate in antineutrinos (2016-06-17 MINERvA W&C suggestive).

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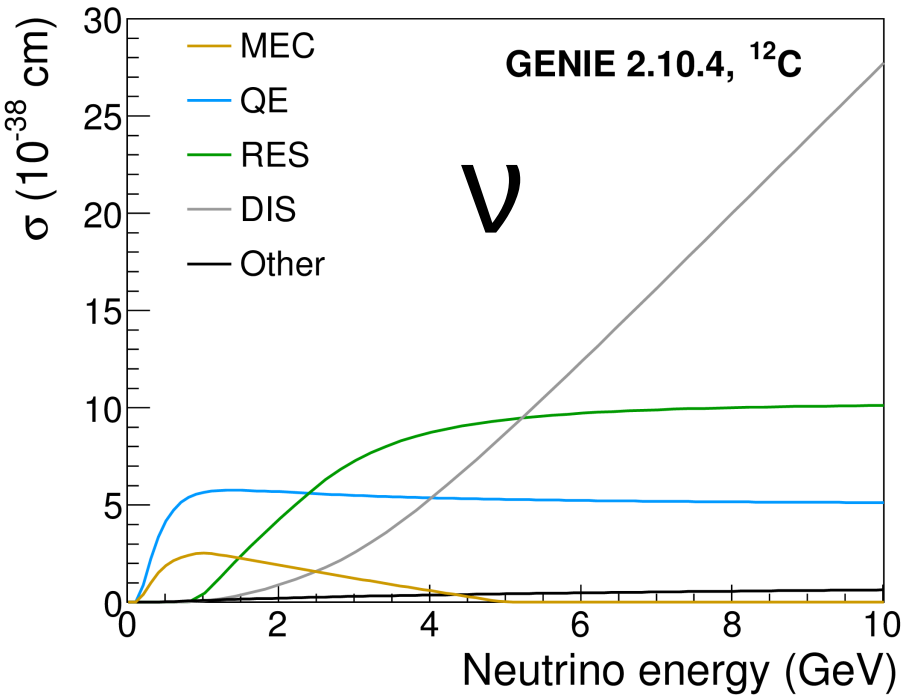
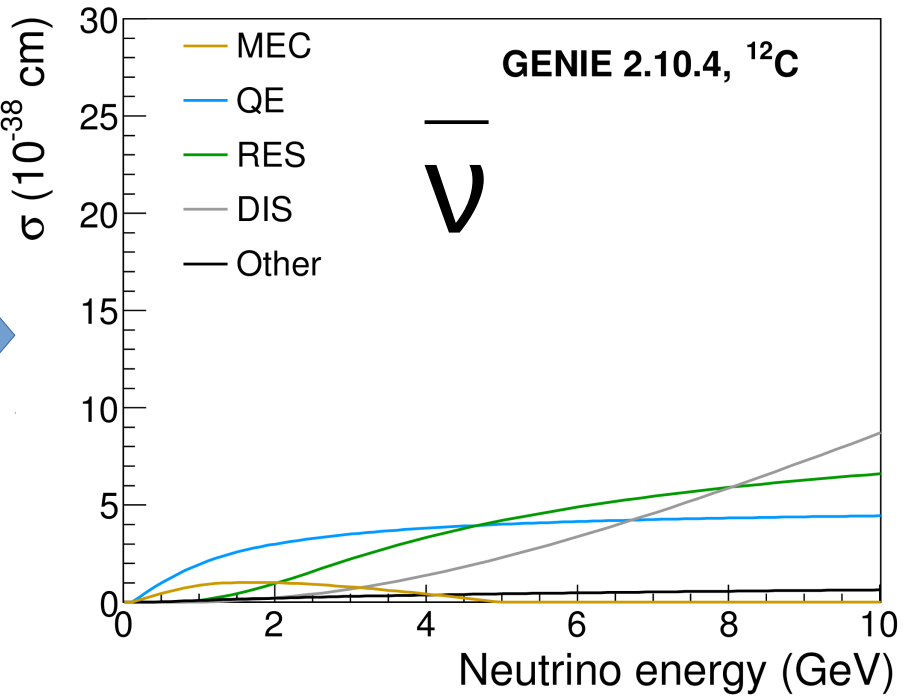
Does the story hold up for $\bar{\nu}$?





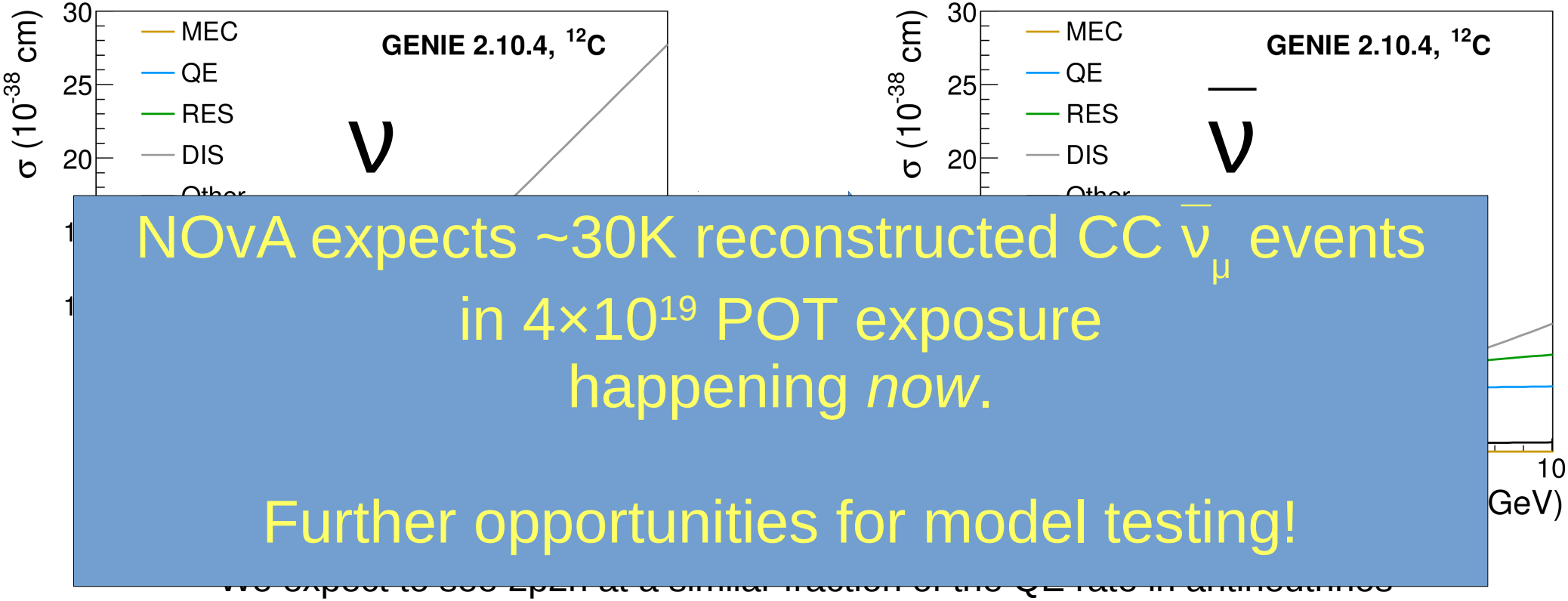
We expect to see 2p2h at a similar fraction of the QE rate in antineutrinos (2016-06-17 MINERvA W&C suggestive).

Crucially,

$np \rightarrow pp$ $\qquad$ $np \rightarrow nn$

So **the visible hadronic state is qualitatively different**.

Open questions:
Does the story hold up for $\bar{\nu}$?



NOvA expects ~30K reconstructed CC $\bar{\nu}_\mu$ events in 4×10^{19} POT exposure happening *now*.

Further opportunities for model testing!

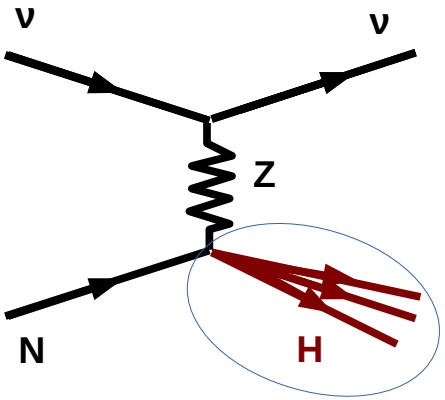
(2016-06-17 MINERvA W&C suggestive).

Crucially,

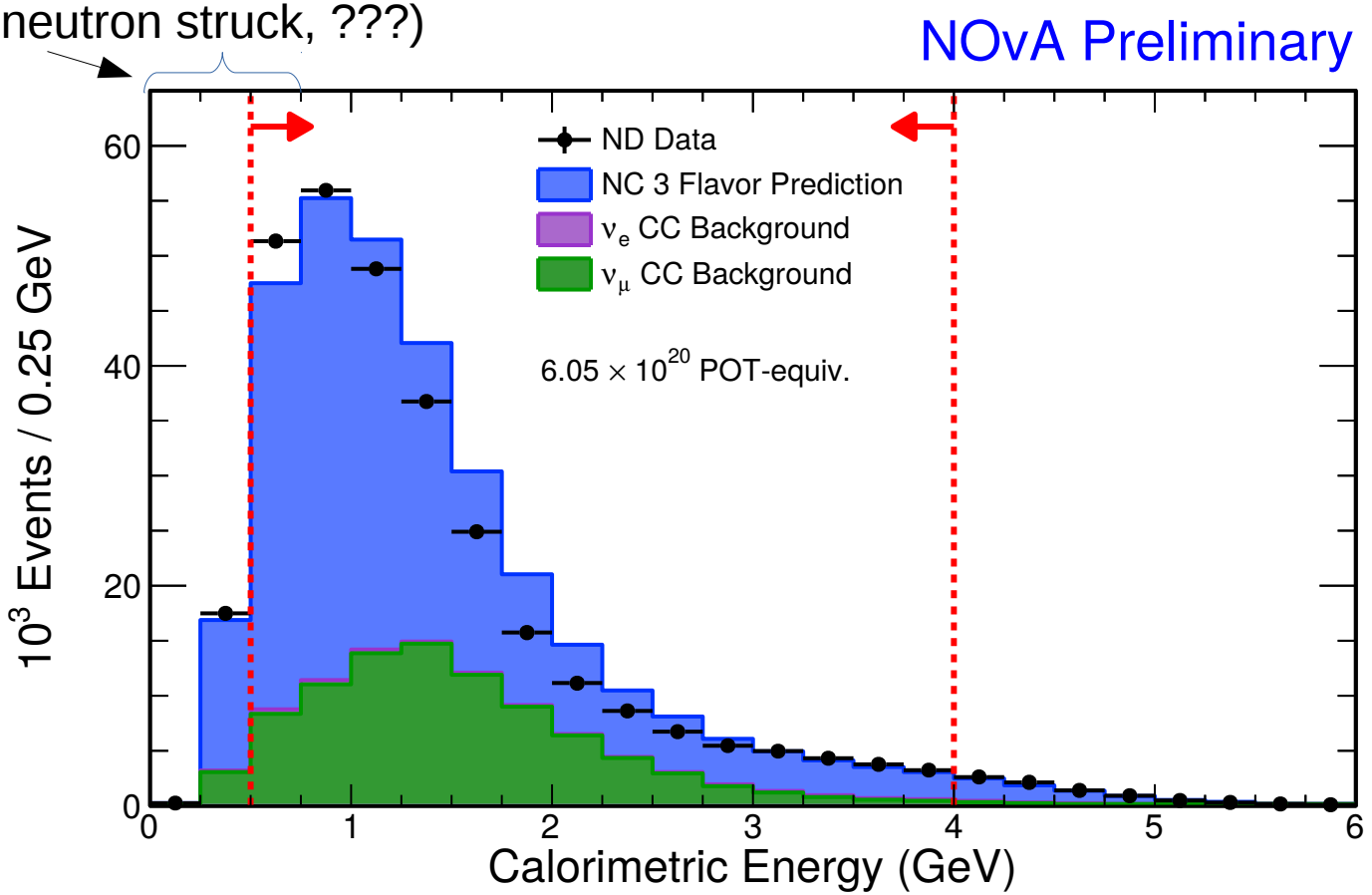
$np \rightarrow pp$ ⇒ $np \rightarrow nn$

So **the visible hadronic state is qualitatively different**.

Open questions: What about NC?



We expect 2p2h to show up hereish
(*np* pair: if proton struck, should be visible;
if neutron struck, ???)



"Empirical MEC" doesn't do NC.
Even if it did, **we couldn't tune it the same way**
(can't reconstruct all of $\underline{q}$ four-vector without lepton)

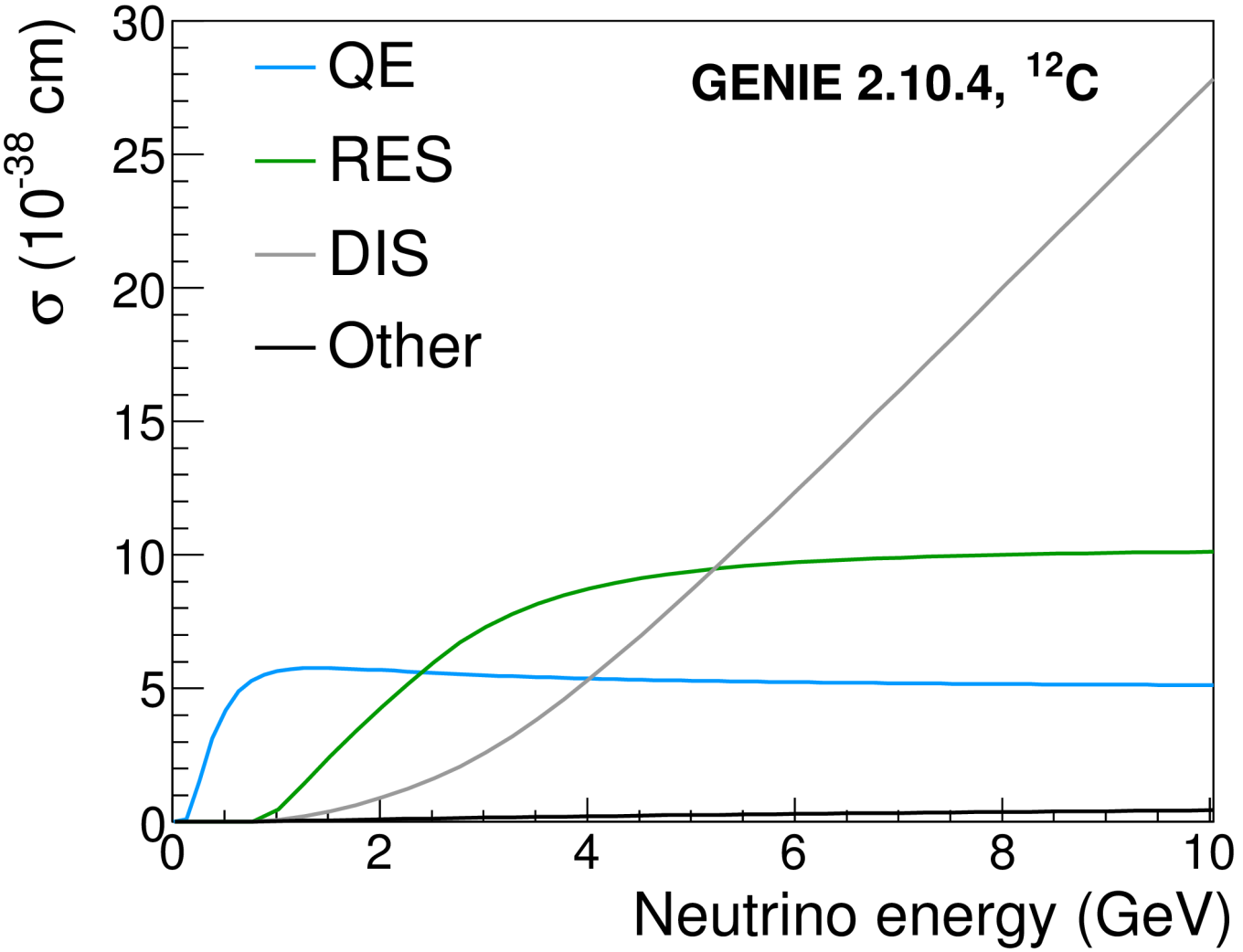
Summary

- NOvA has found that tuning GENIE 2.10.4 can vastly improve prediction of ν_μ CC inclusive spectrum:
  - Use of optional “empirical MEC” model, tuned to ND data, to provide 2p2h events
  - Reduction of single nonresonant pion production at low W per external re-evaluation of bubble chamber data
- We expect to consider and incorporate near-term improvements to GENIE into our tuning procedures:
  - Model(s) for 2p2h in all channels (CC ν, $\bar{\nu}$; NC)
  - Other alternative models? (coherent, QE strange production, …)
- We look forward to improved default model(s) coming with GENIE 2.12, 3.0, and beyond!

Thank you on behalf of NOvA!

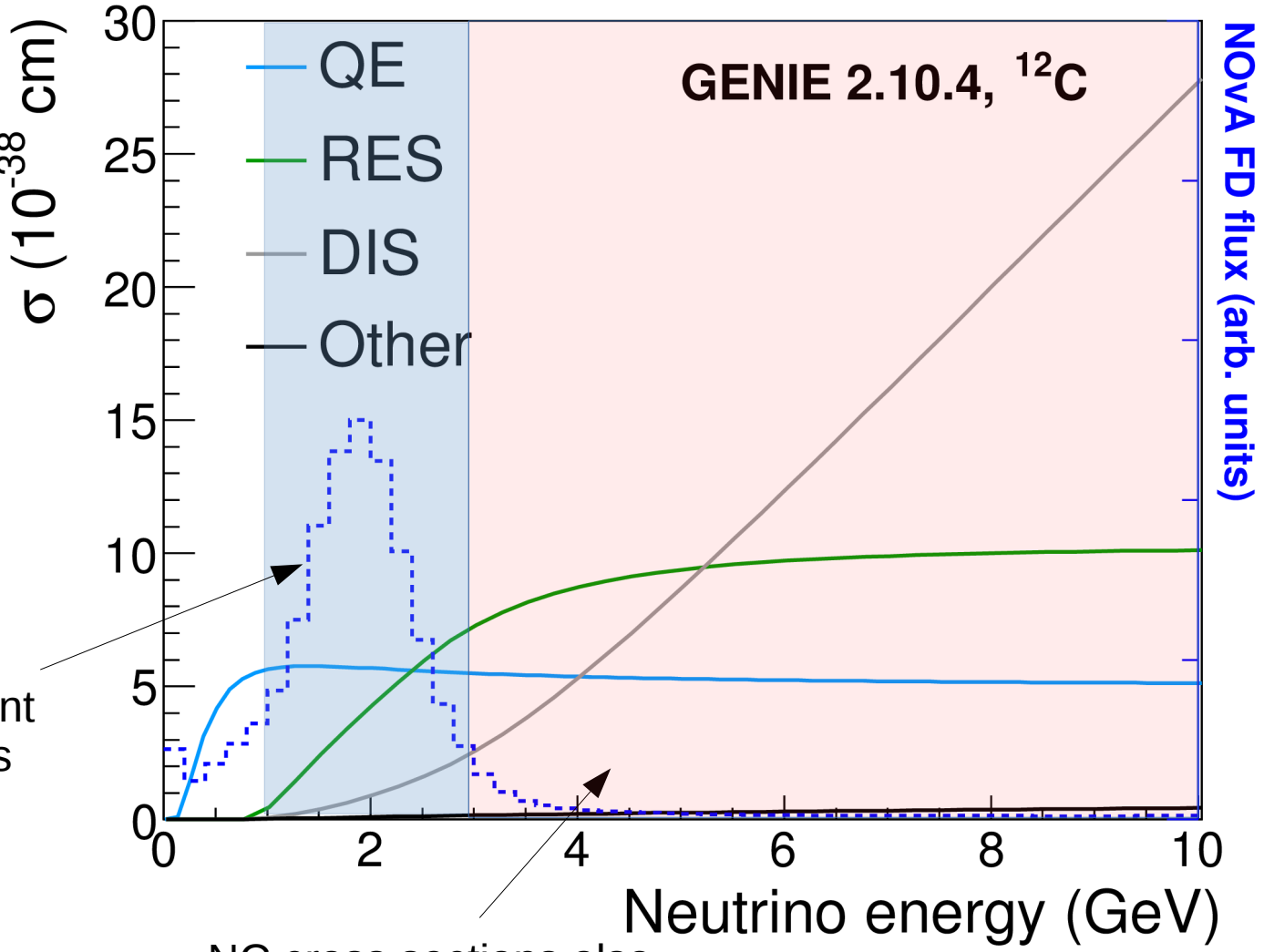
Backup slides follow

NOvA and cross section models



NOvA detectors are primarily carbon, with some Cl and other stuff at lower levels.
Used to thinking about “big three” in cross sections...

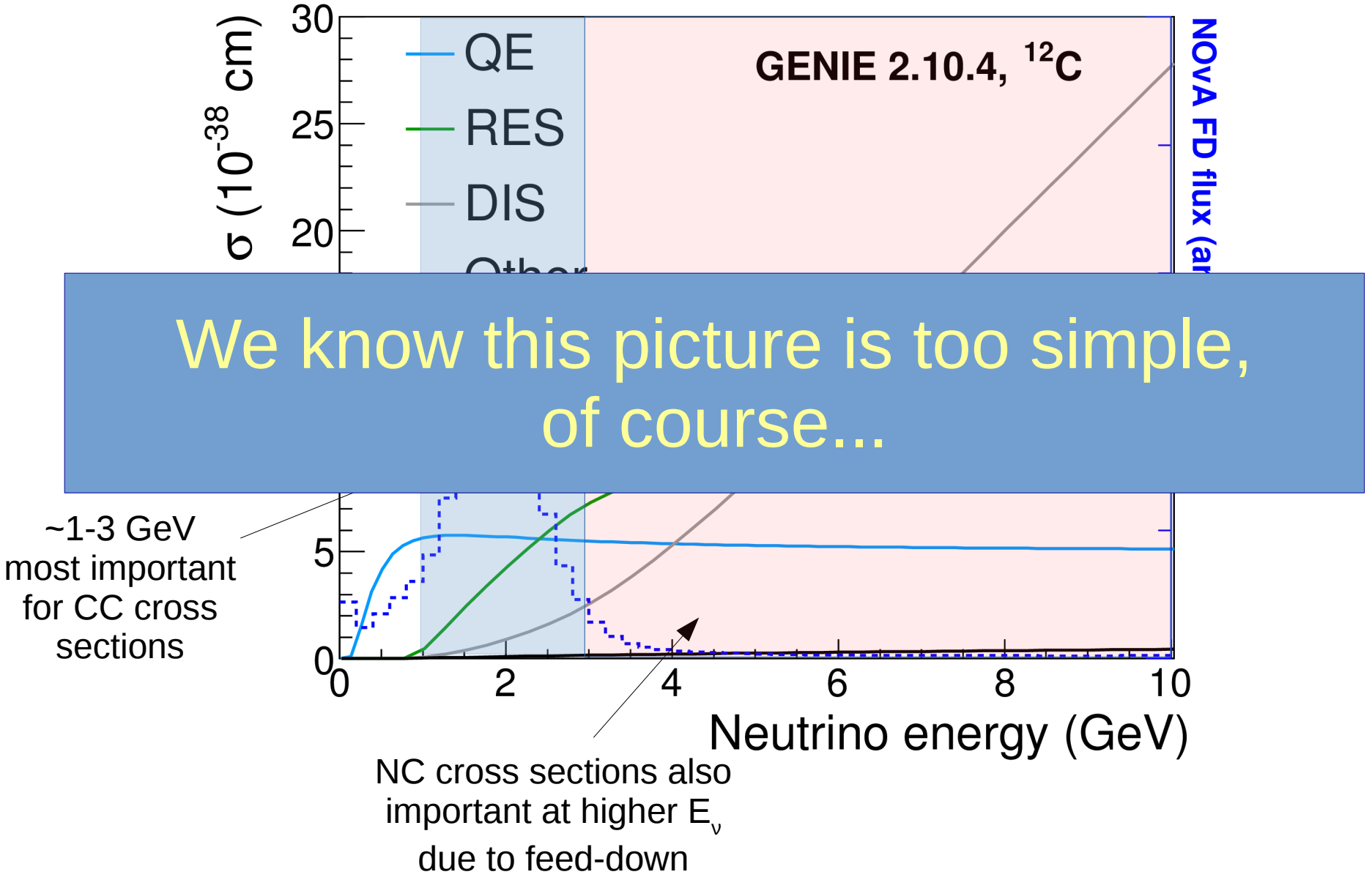
NOvA and cross section models



~1-3 GeV most important for CC cross sections

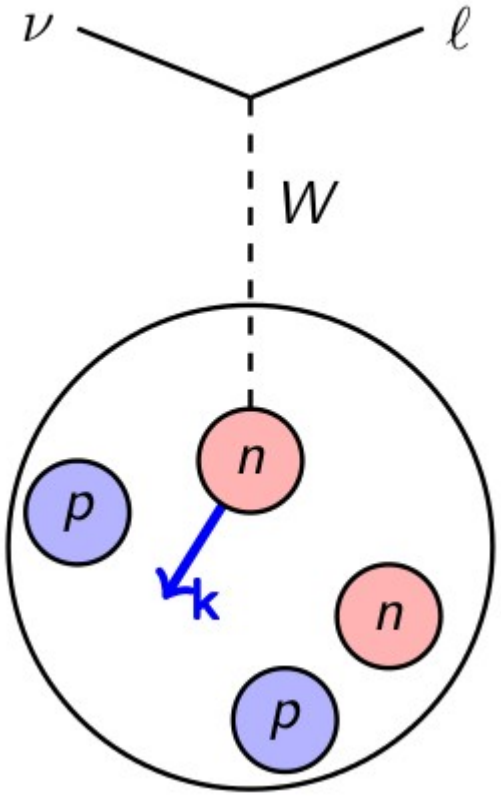
NC cross sections also important at higher E_ν due to feed-down

NOvA and cross section models

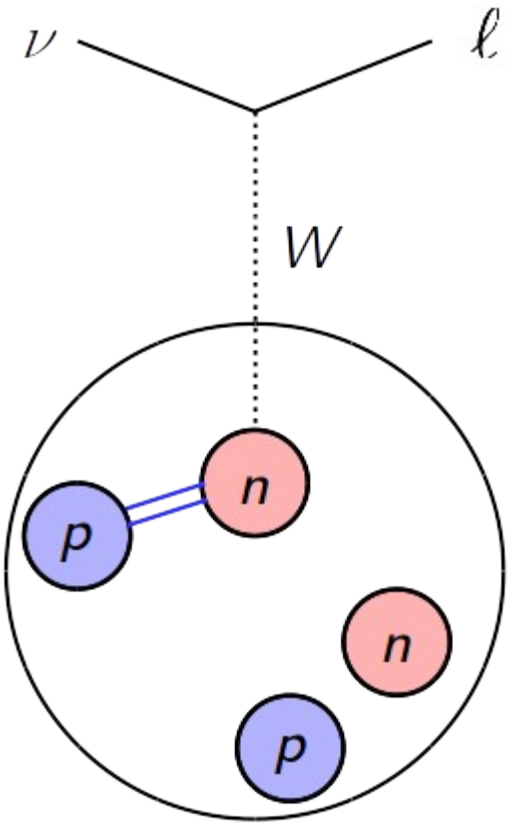


Not so fast...

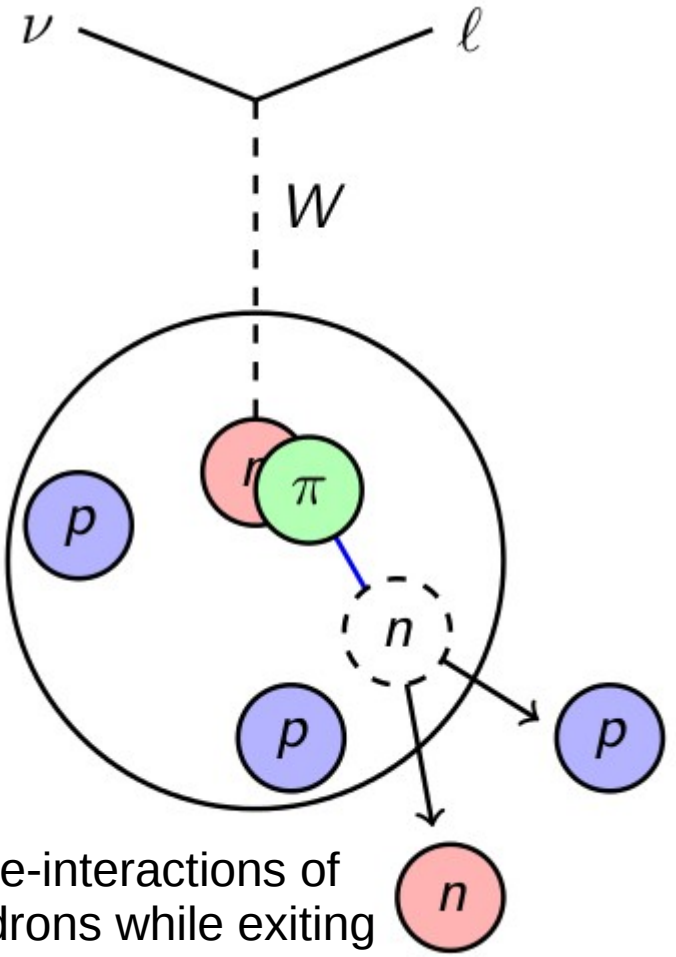
[Figs. courtesy P. Rodrigues]



Initial nucleon momentum due to nuclear potential



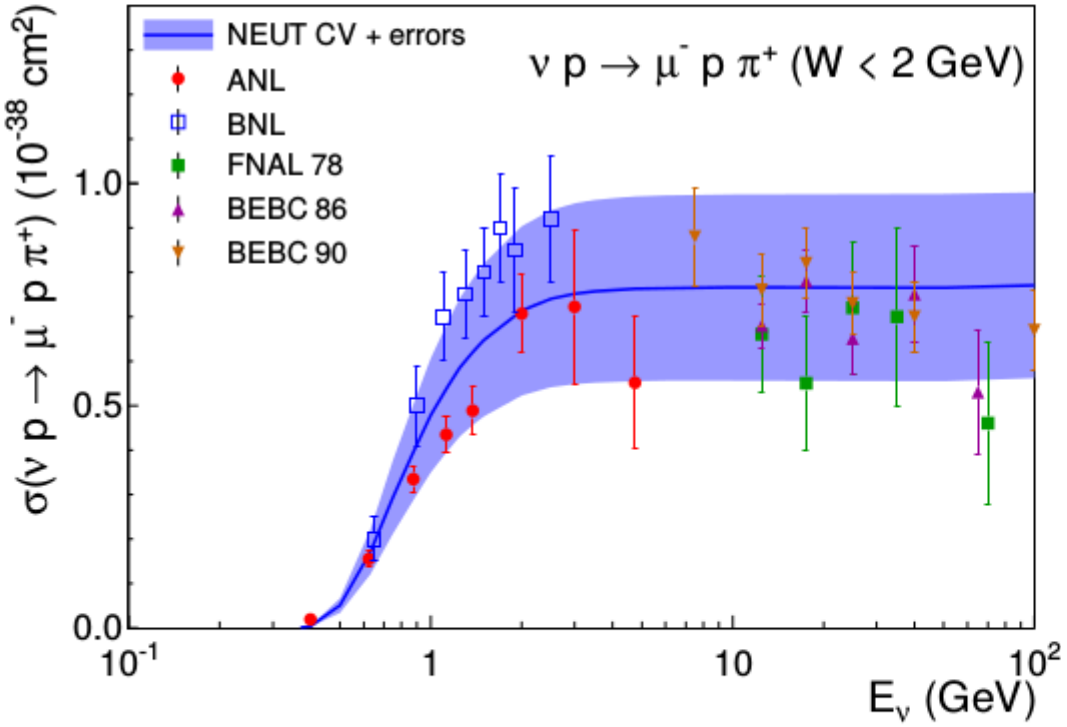
Interactions and/or substructure within the nucleus



Re-interactions of hadrons while exiting the nucleus

The nuclear environment alters otherwise straightforward cross sections in pernicious and sometimes subtle ways

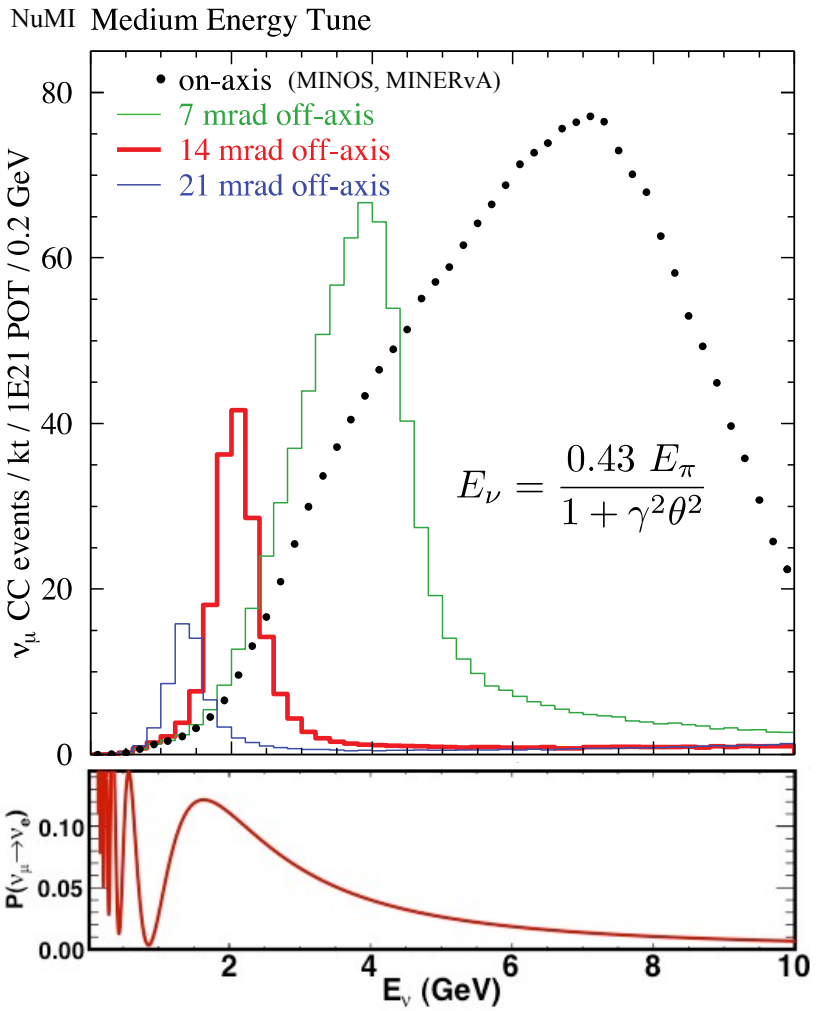
Not so fast...



[fig. courtesy P. Rodrigues] NEUT prediction

And even data from scattering on "simple" targets sometimes presents difficulties...

NuMI beam design



Baseline (L = 810 km)

The neutrino beam travels from Fermilab to Ash River, MN through the earth's crust.

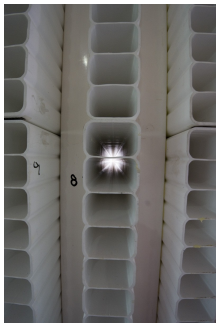
Energy (E_ν = 2 GeV)

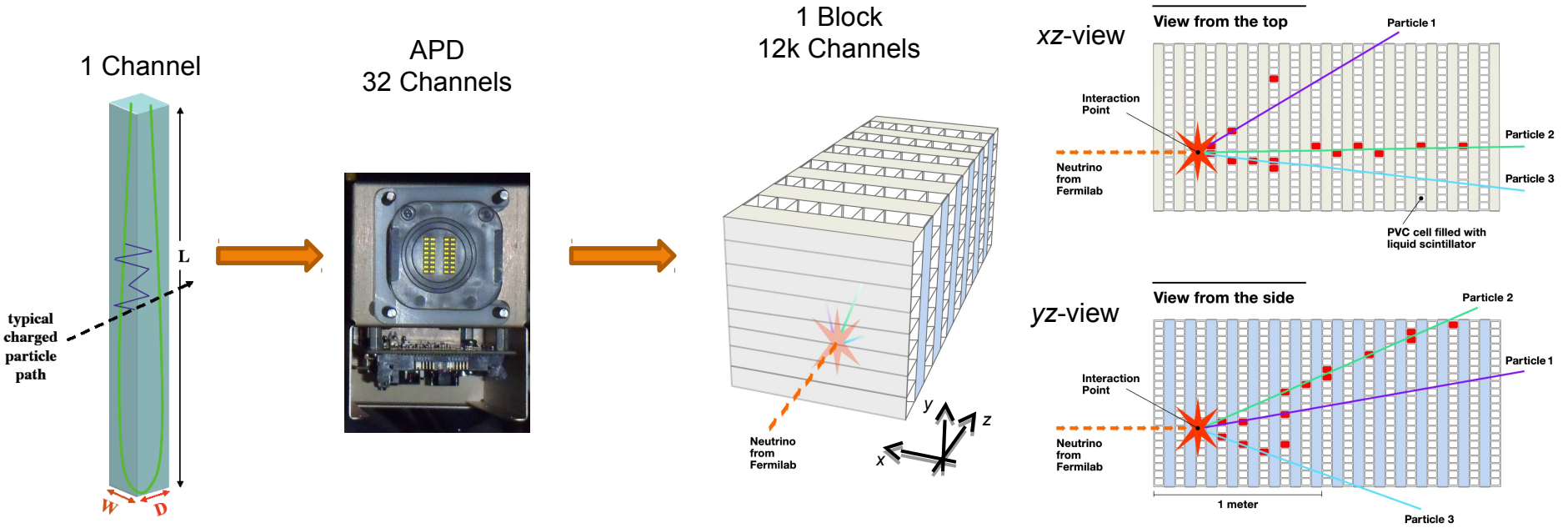
We can achieve a narrowly distributed neutrino energy by placing the far detector 14.6 mrad off the beam axis.

This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.

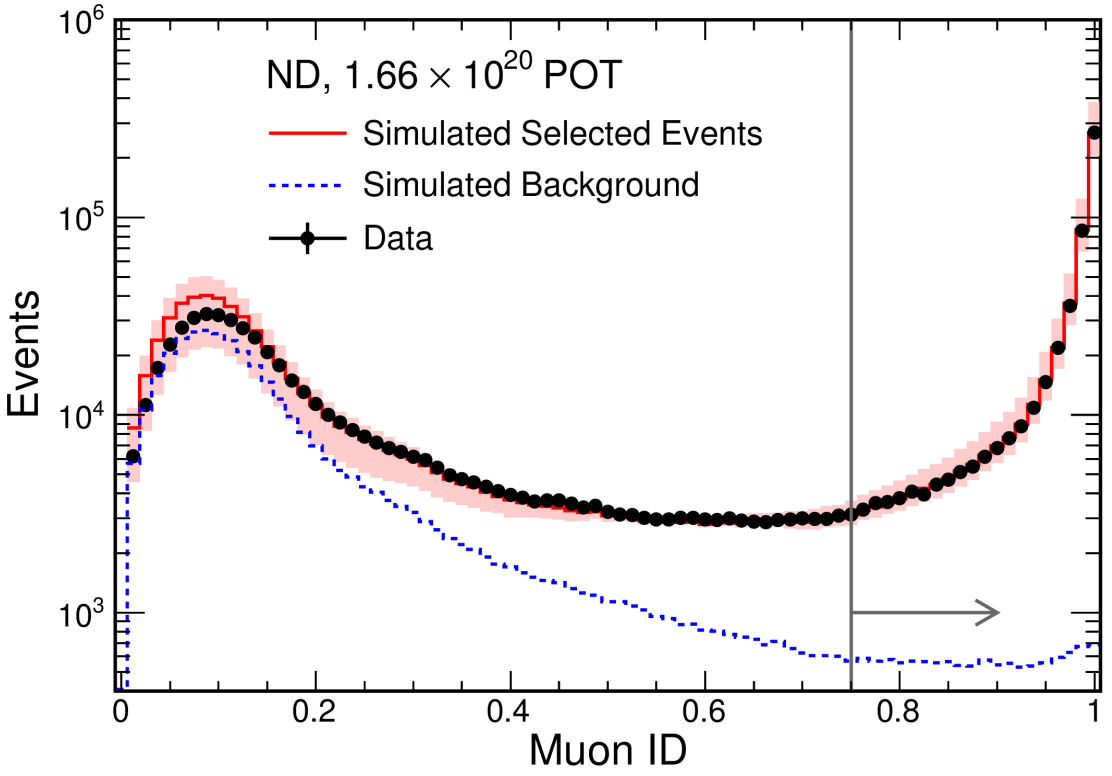
NOvA detector design

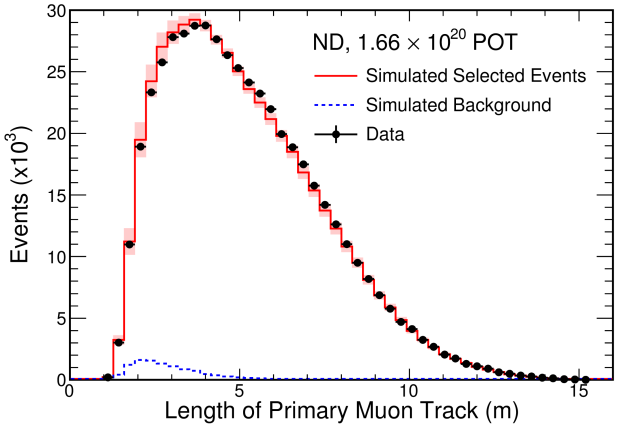
- "Fully" active detector enables good energy resolution for electromagnetic, hadron showers
  - use low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides many samples per radiation length (differentiate e^- and π^0)
  - each extrusion contains one wavelength-shifting fiber
  - ends of fiber read out by avalanche photo-diode (APD)

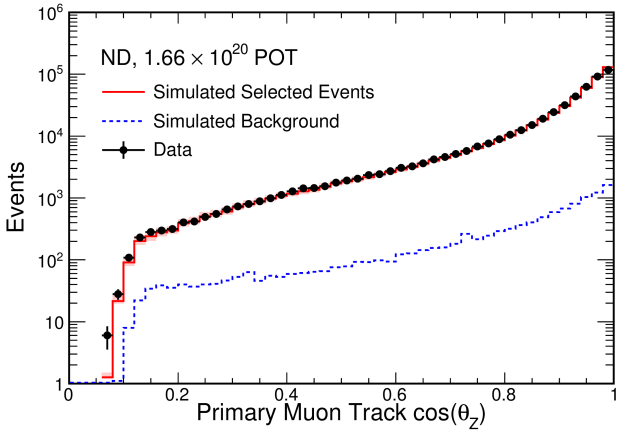




Selecting ν_μ CC events







4-variable kNN used for muon identification:
Track length
dE/dx along track
scattering along track
track-only plane fraction

Muon kinematics simulated well

Also enforce containment in interior of detector volume