Neutrino cross-section tuning in

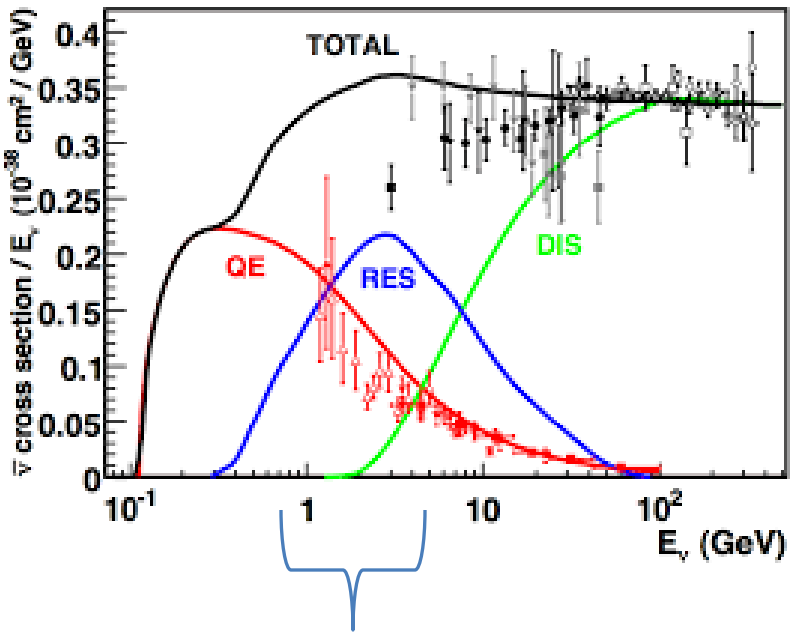
Kirk Bays (IIT)

NuFact 2022

August 2, 2022

Introduction

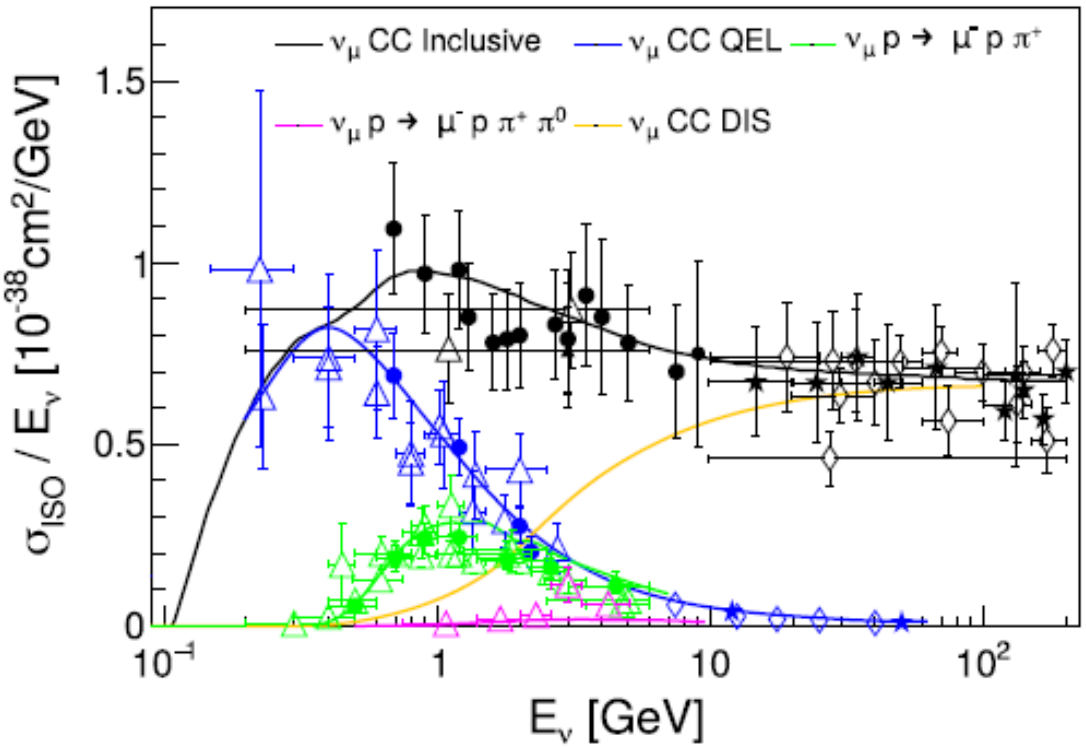
- Even with 2-detector designs, accurate **modeling necessary to prevent biases** and large uncertainties
- Models aren't perfect!
- Each experiment must correct models as appropriate, and create comprehensive systematics. This talk is about the NOvA approach



NOvA energy range includes all modes (QE, RES, DIS, MEC)

Starting point

- The latest NOvA results start from GENIE 3.0.6. GENIE 3.2.0 is also now available, which adds many new important models I will mention later



GENIE 3 G18_02a_00_000
hydrogen and deuterium data

Starting point

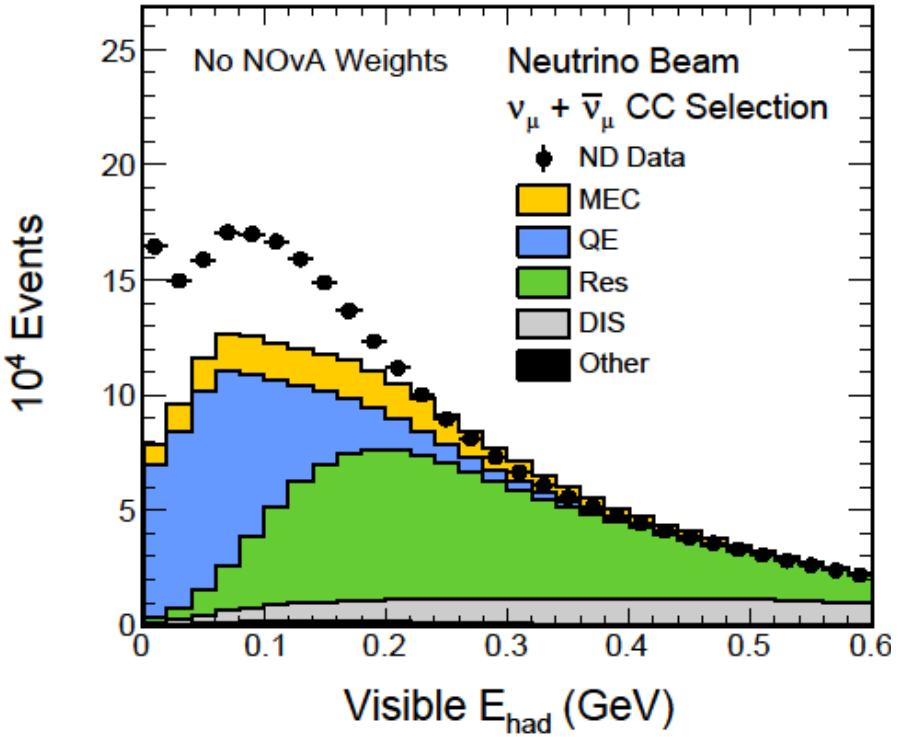
- The latest NOvA results start from GENIE 3.0.6. GENIE 3.2.0 is also now available, which adds many new important models I will mention later

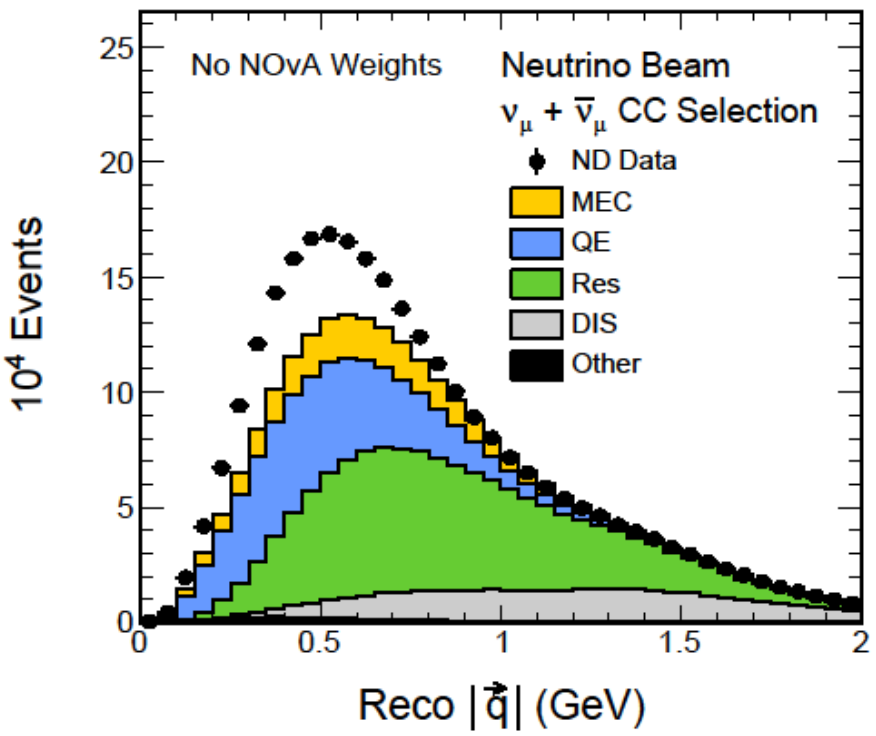
- NOvA GENIE base models:

Process	Model	
QE	Valencia 1p1h	arXiv:1102.2777
RES	Berger-Sehgal	arXiv:0709.4378
DIS	Bodek-Yang	arXiv:1012.0261
2p2h	Valencia 2p2h	arXiv:1102.2777
FSI	hN cascade	doi.org/10.1063/1.3274190

Starting point

GENIE 3.0.6 vs NOvA ND data with no tuning





Starting point

- **<u>Tuning philosophy</u>:**
  - Use any **external data** or **theory improvements** we can beyond what GENIE has included
  - Look for **disagreements with our own data**
  - Ensure our **systematics cover**

- Look at each model individually:
  - QE / RES / DIS / MEC / FSI

Quasi-elastic interactions

- Central value: Valencia QE includes RPA (nuclear screening) effects. There is **no *a priori* reason to believe tuning is necessary**
- Uncertainties: We use the **Z-expansion** formalism, an improvement on old dipole form factor uncertainties new in GENIE 3. Also **RPA systematics**
- NOvA modifications: none

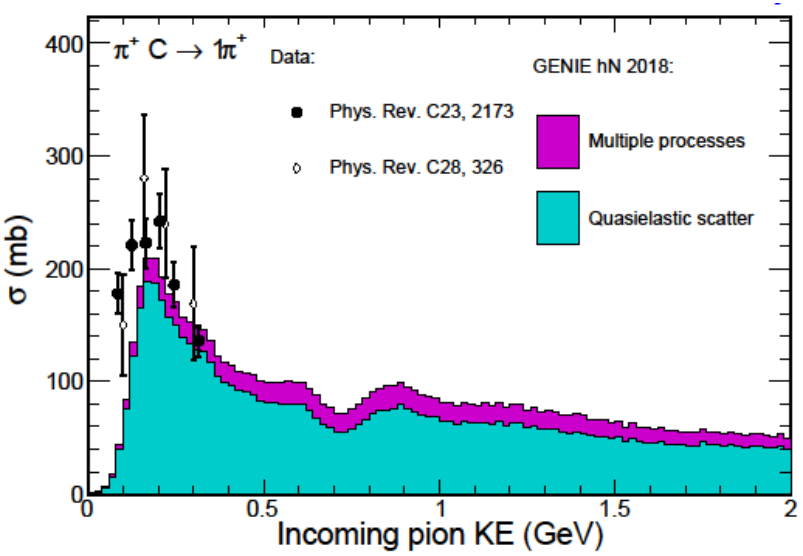
Z-expansion: doi.org/10.1103/PhysRevD.93.113015

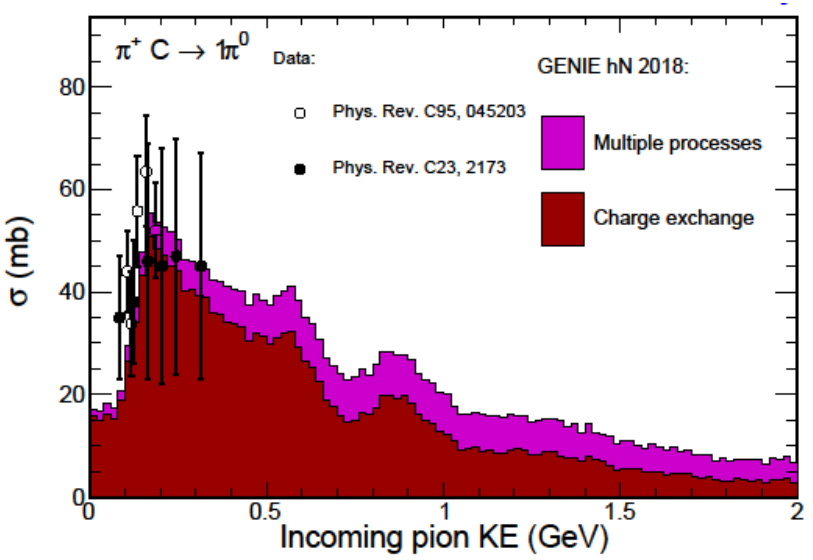
RES and DIS interactions

- Central value: GENIE 3 comes with a tune of RES and DIS to data that we use (02_11a). **No reason to expect changes are needed**
- Uncertainties: **generous uncertainties included in GENIE** (dipole form-factor and normalization)
- NOvA modifications: minimal increases in DIS normalization systematics

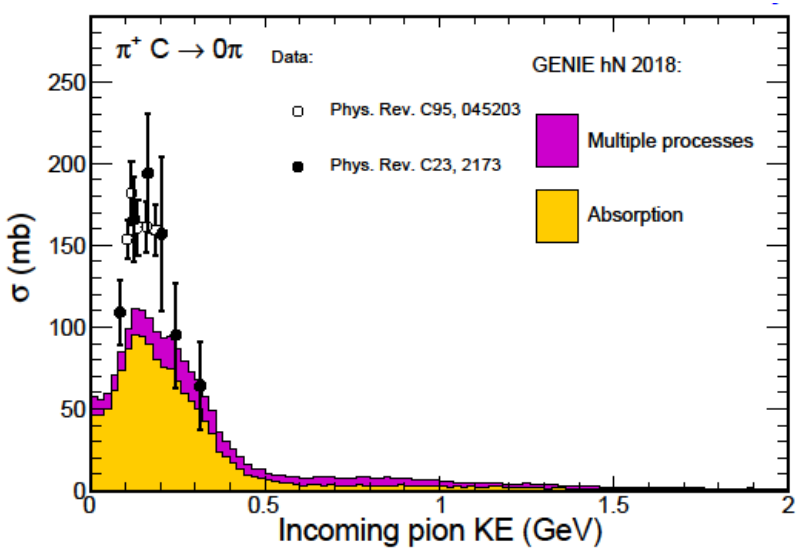
Final state interactions

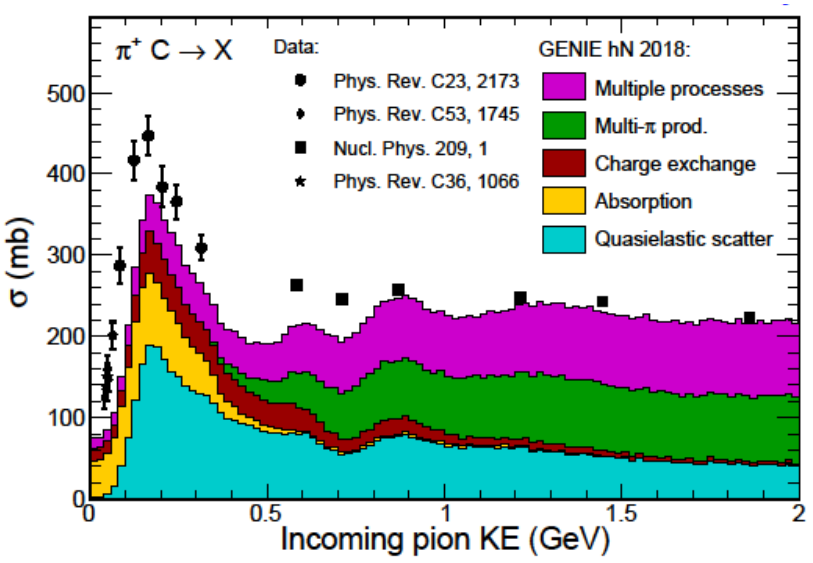
- FSI is *hard*; often largest model uncertainty
- GENIE 3.0.6 has two options; we use hN cascade model
- Comparing GENIE simulation with external data (doi.org/10.1016/0375-9474(88)90310-7), broken into subsamples, we see discrepancies that motivate a central value tweak
- T2K uses a similar model and did a fuller analysis fitting to similar data (doi.org/10.1103/PhysRevD.99.052007); we piggy-back on this work and use the uncertainties they found

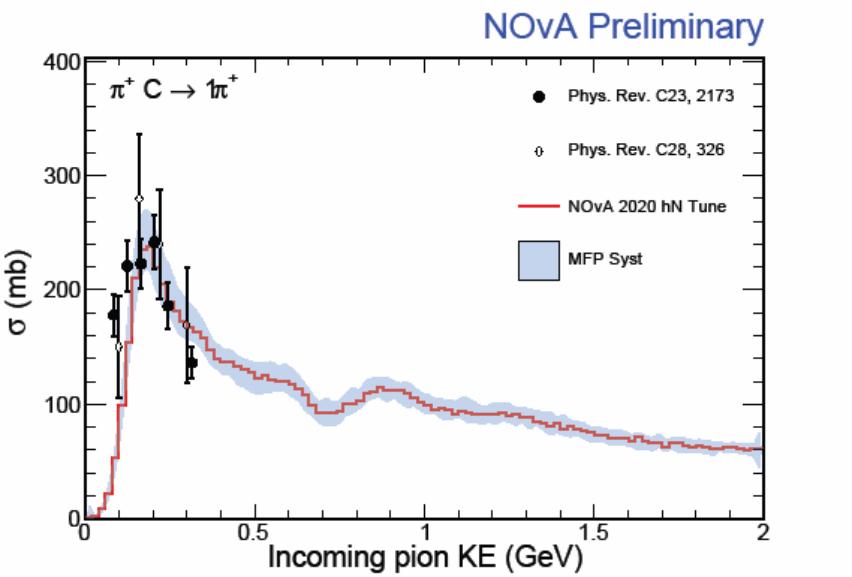




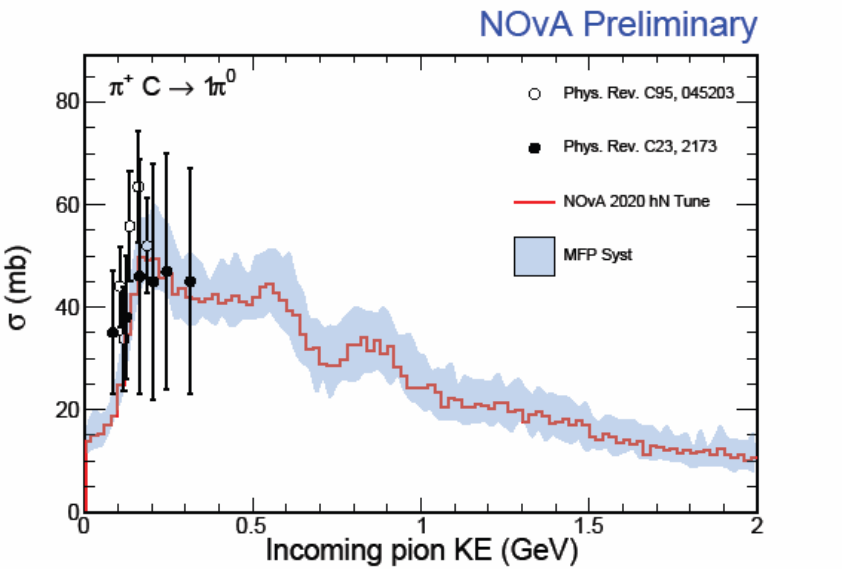
Before tuning





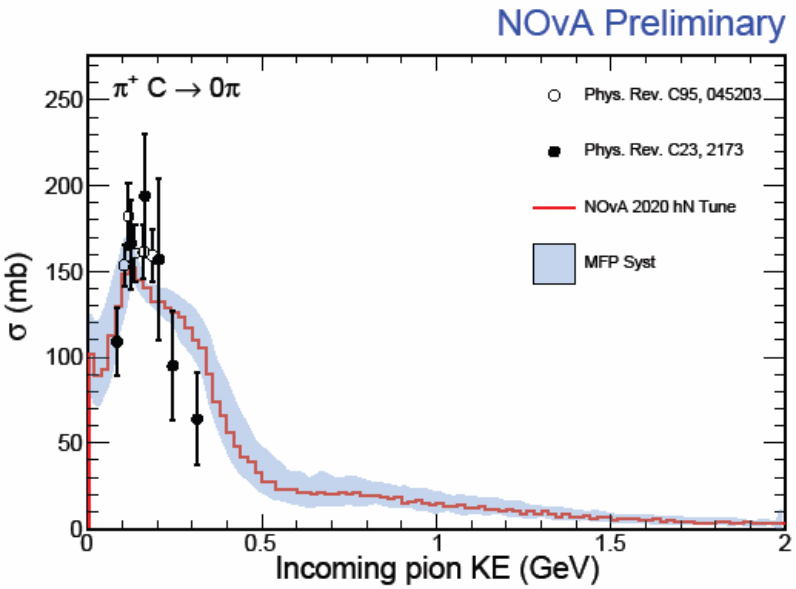


-10%

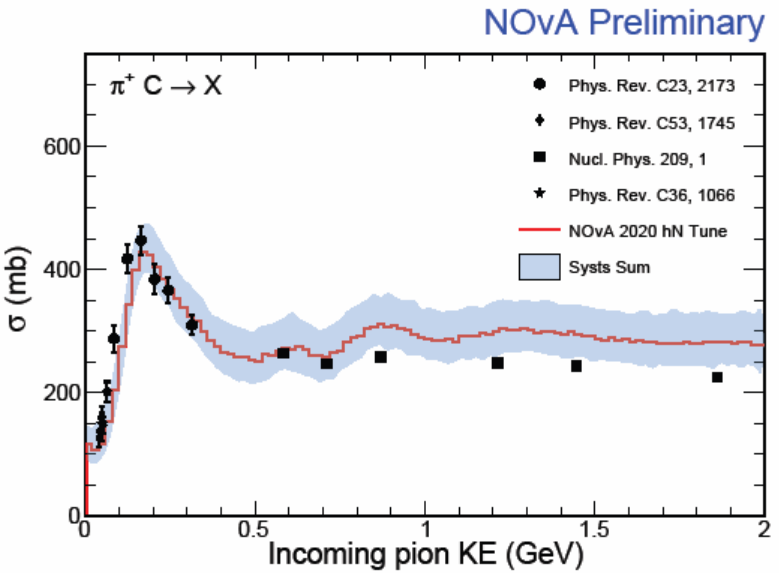


-30%

After tuning, with uncertainties



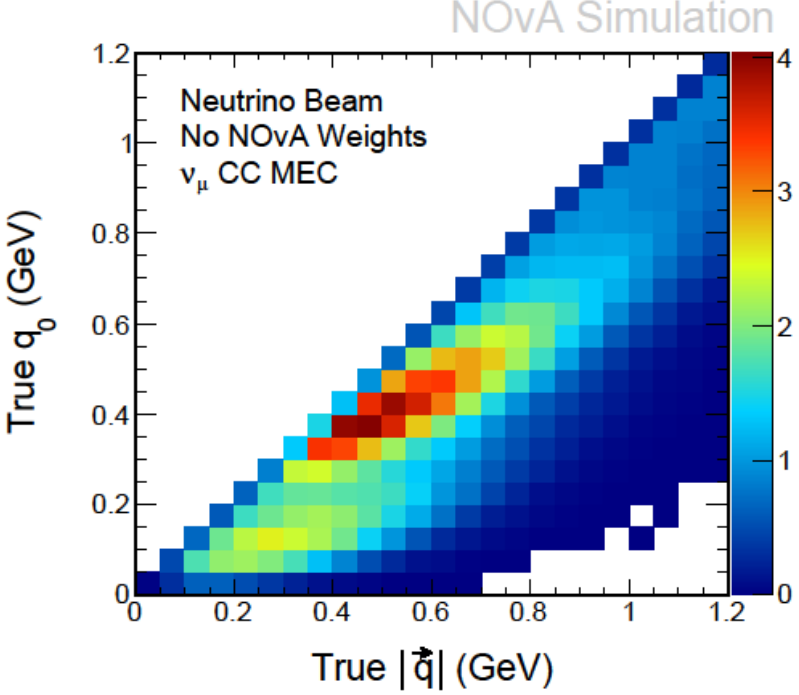
+40%

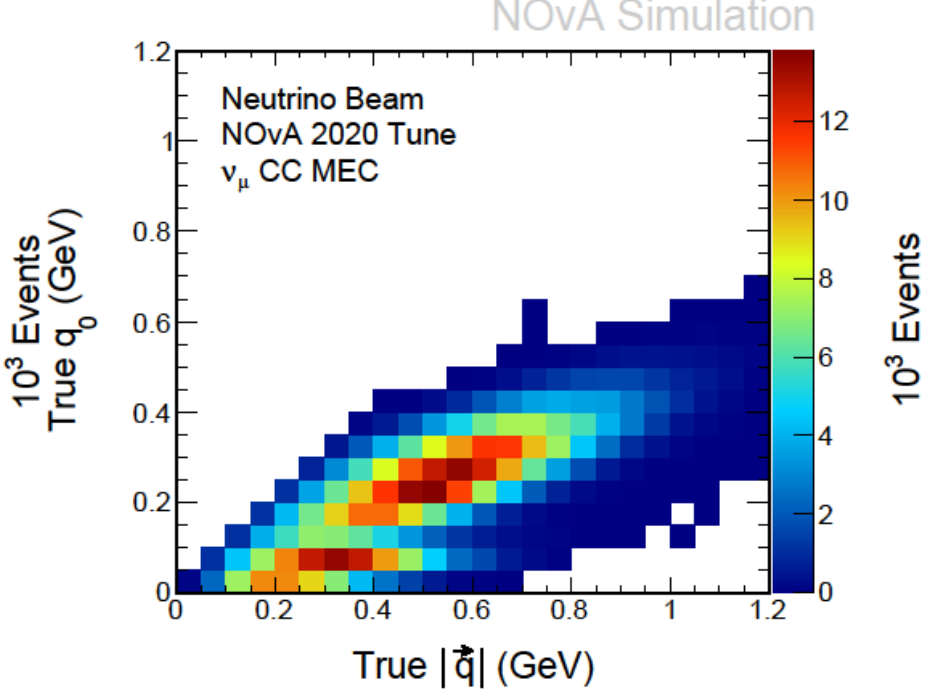


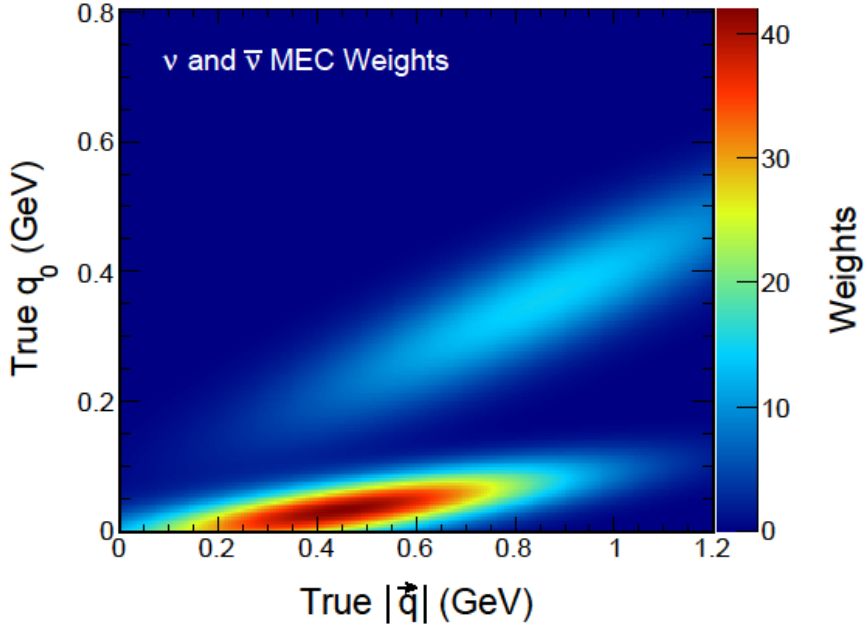
+40%

MEC

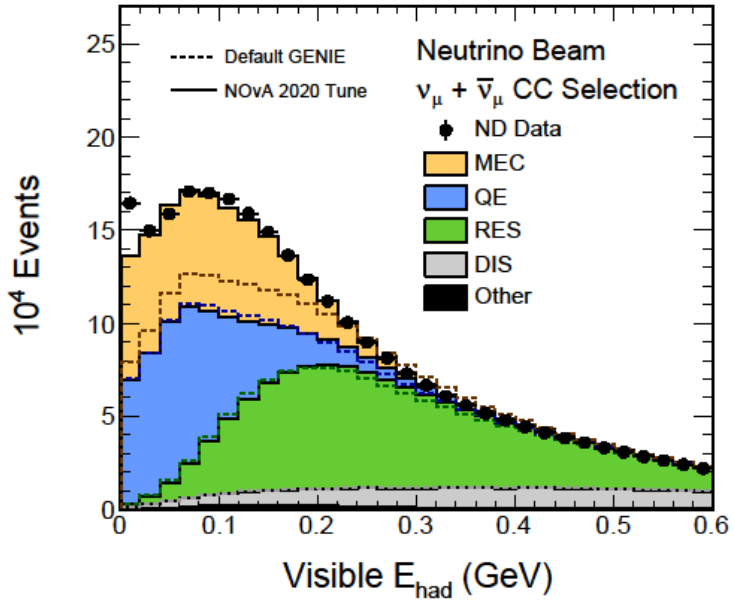
- Current **2p2h models do not agree with data**, as seen in NOvA and many other experiments
- NOvA philosophy: after other tuning, consider **all remaining disagreements between simulation and** NOvA ND **data** to be **due to MEC**, and tune the MEC model such that it fits the data, with generous uncertainties added
  - Purely empirical approach
- Fit: use two 2-D Gaussians to fit in momentum and energy transfer space. Use same tune for neutrino- and antineutrino-mode

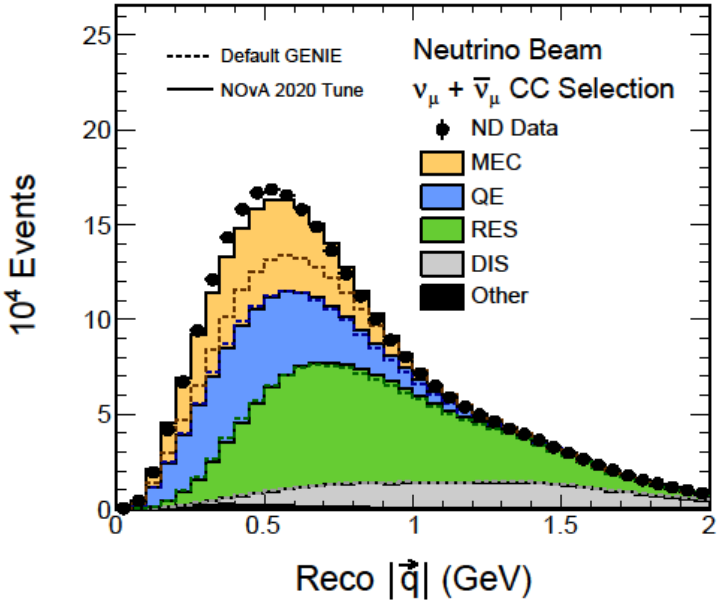


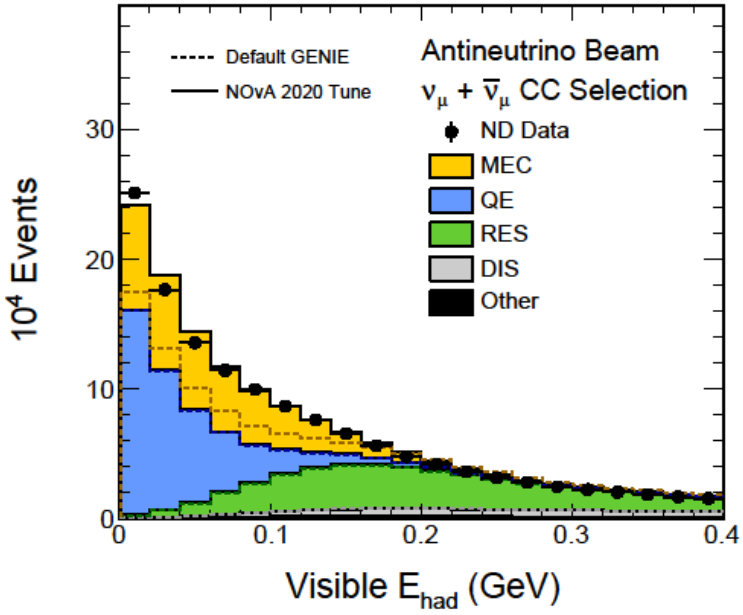


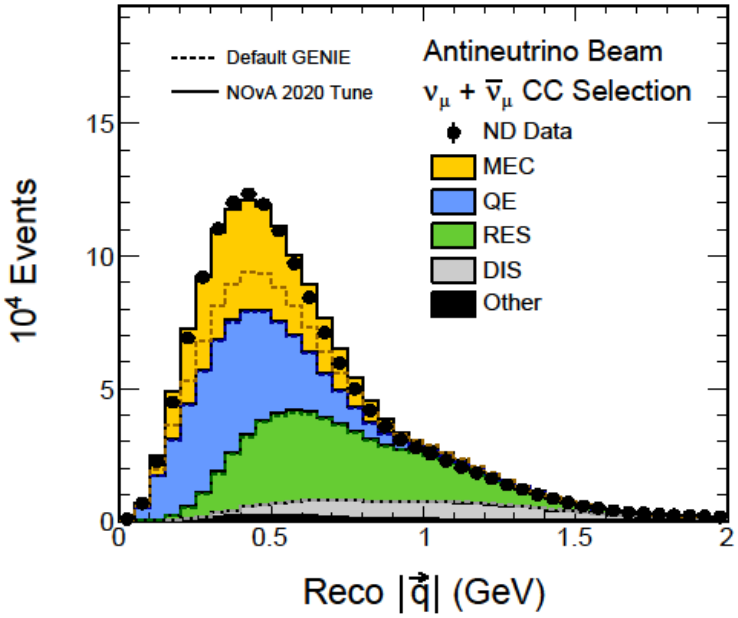


Component	Parameter	Fitted value
Gaussian 1	Normalization	14.85
	Mean q_0	0.36
	Mean $\|\vec{q}\|$	0.86
	Sigma q_0	0.13
	Sigma $\|\vec{q}\|$	0.35
	Correlation	0.89
Gaussian 2	Normalization	42.0
	Mean q_0	0.034
	Mean $\|\vec{q}\|$	0.45
	Sigma q_0	0.044
	Sigma $\|\vec{q}\|$	0.31
	Correlation	0.75
Base model	Normalization	-0.08


Default GENIE
NOvA 2020 Tune
Neutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Visible E_{had} (GeV)


Default GENIE
NOvA 2020 Tune
Neutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco $|\vec{q}|$ (GeV)


Default GENIE
NOvA 2020 Tune
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Visible E_{had} (GeV)

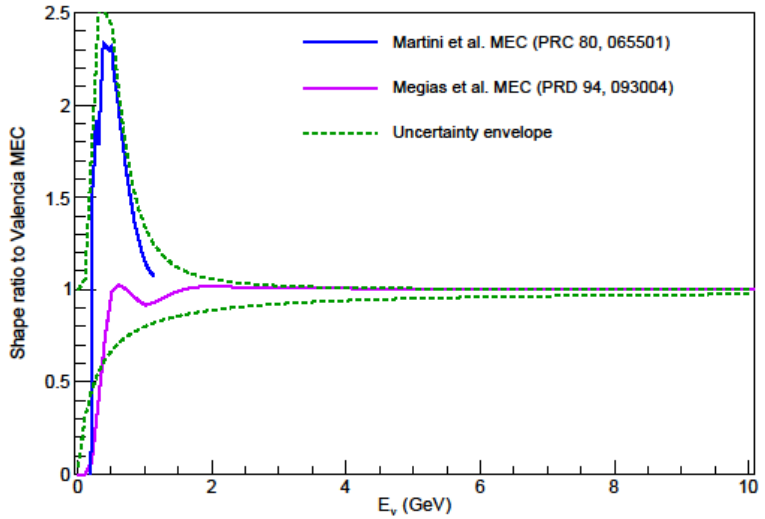

Default GENIE
NOvA 2020 Tune
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco $|\vec{q}|$ (GeV)

MEC uncertainties 1 and 2

- Two theory-based uncertainties:
- 1) cross-section: an **energy-dependent normalization uncertainty** based on an envelope encapsulating different models
- 2) the ratio of struck nucleons changes by model; we add uncertainty as:

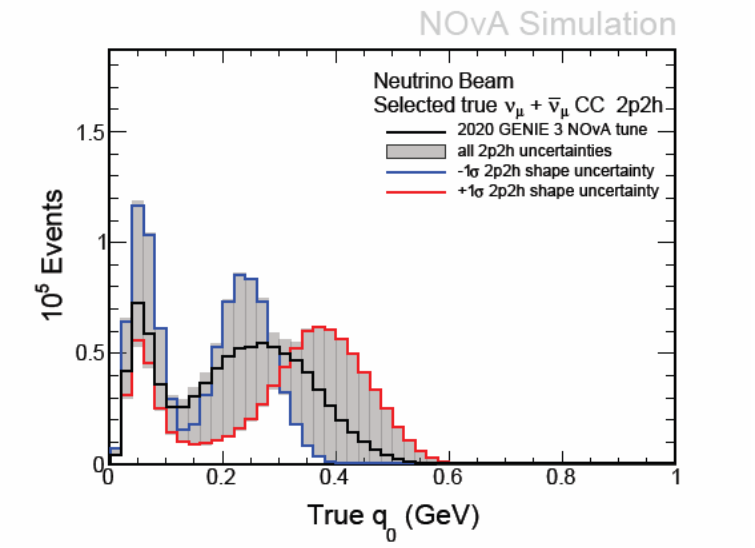
ν: $$\frac{np}{np+nn} = 0.69 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

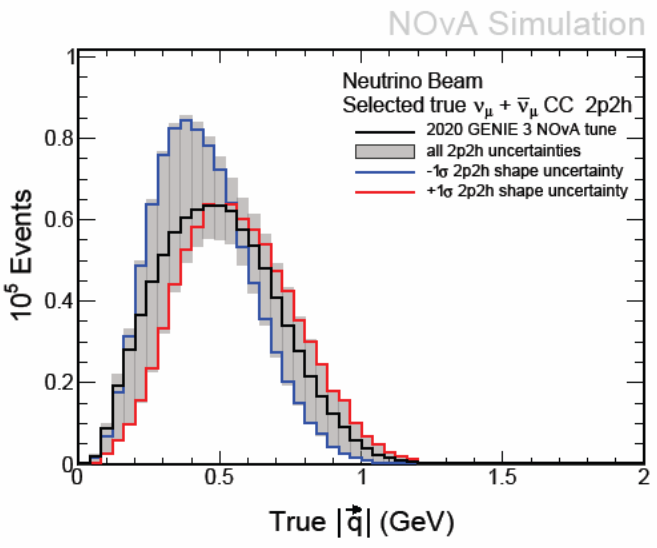
anti–ν: $$\frac{np}{np+pp} = 0.66 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

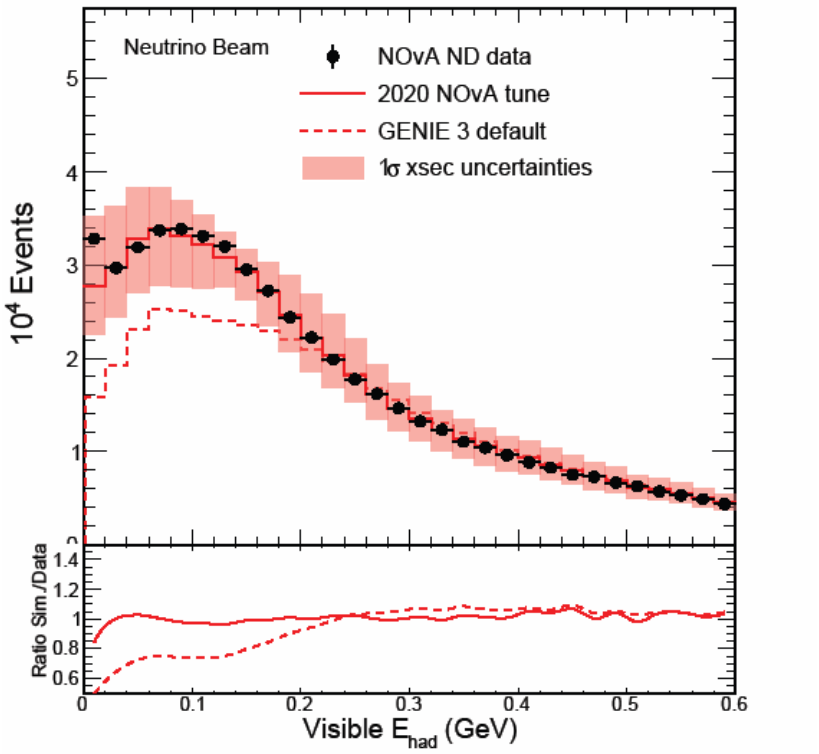


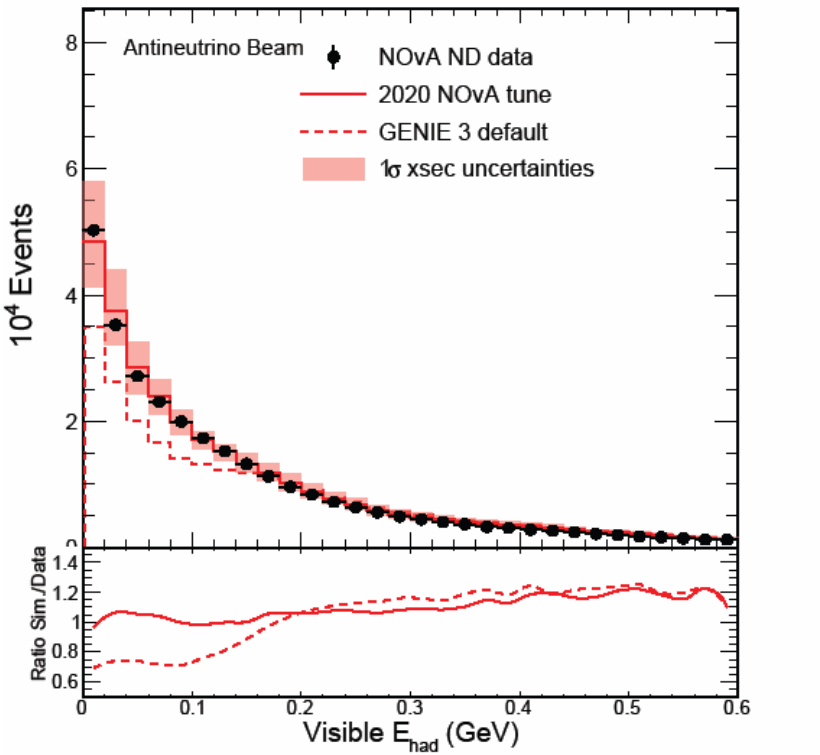
MEC uncertainty 3

- Want to **conservatively bracket** any **remaining uncertainty**
- If our other simulation were perfect, tuning to our ND data would correctly produce MEC. If our simulation is off, our resultant MEC model can be off
- To estimate**, shift our largest other cross-section uncertainties by 1σ in conjuction** 'up' or 'down' in hadronic energy, **then re-fit**. These are new +/- 1σ uncertainties.





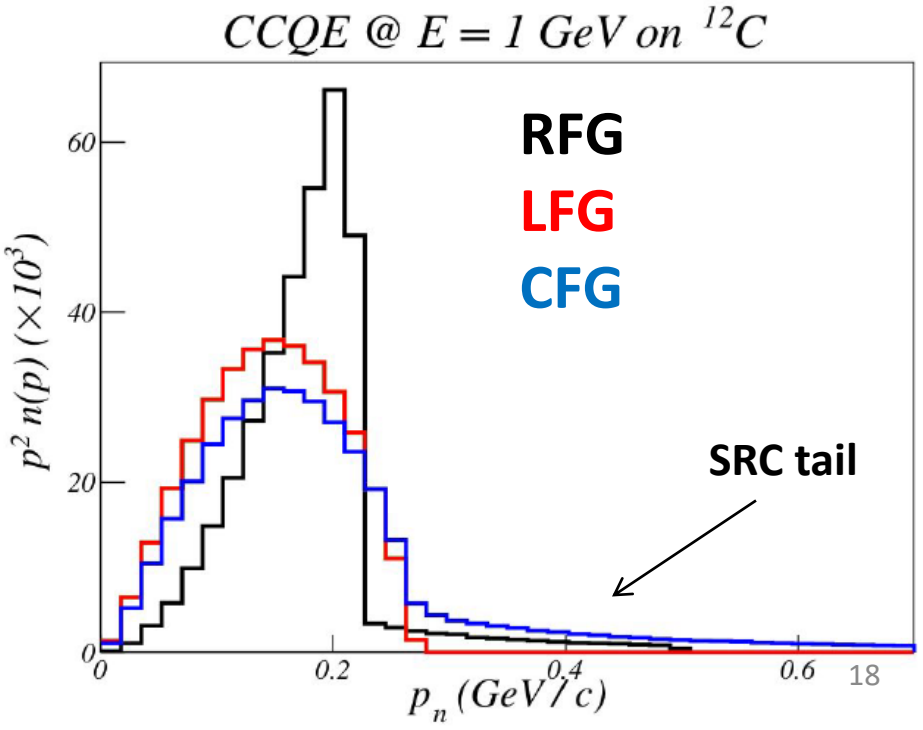




- **Final agreement is good, and well-covered by systematic uncertainties**
- But can we do better?
- What follows are NOT NOvA results, but just ideas we are speculating about

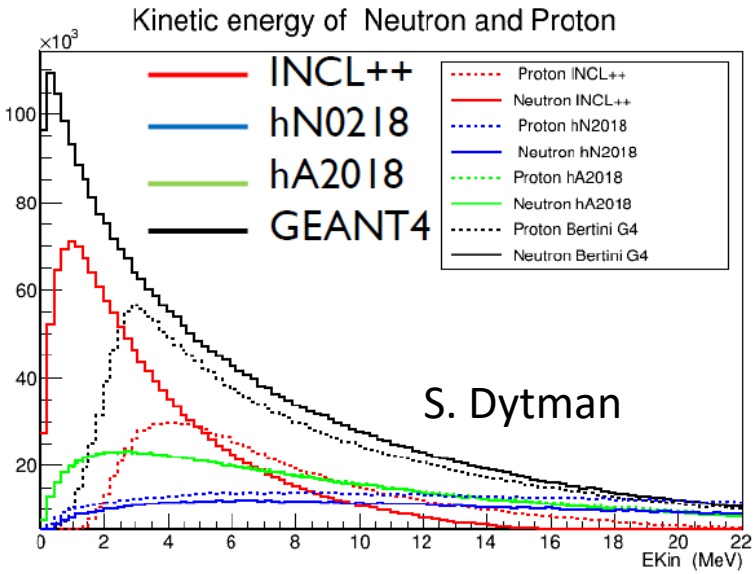
Initial nuclear state:

- Currently use LFG, but this ignores high-momentum tail of SRC we expect to be there
- CFG model in GENIE 3.2.0 an important upgrade
- Worth creating a new initial state uncertainty?
- Affects mostly QE, but also other modes



Better FSI models

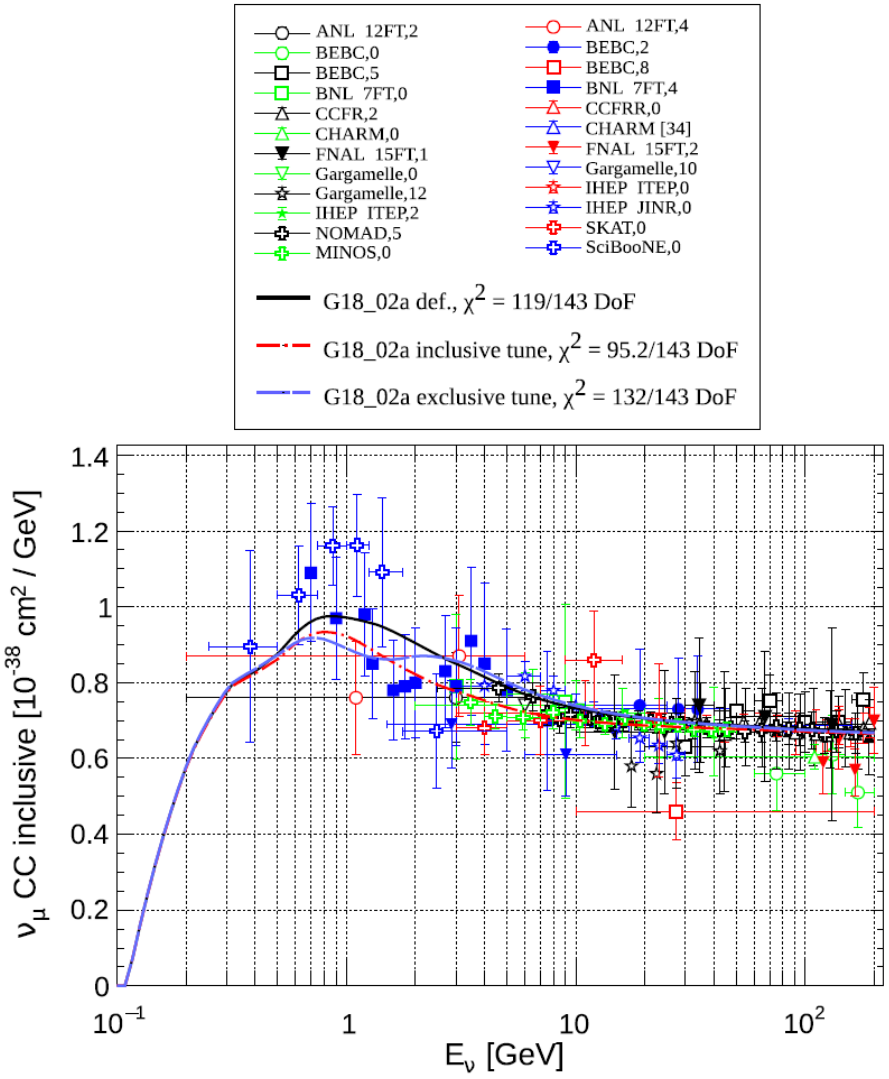
- GENIE 3.2.0 includes new FSI models like INCL++ that are not only more theoretically sophisticated, but also add entirely new low-energy physics channels currently missing
- Also greatly impacts nucleon kinetic energy at low energy



1 GeV on Argon

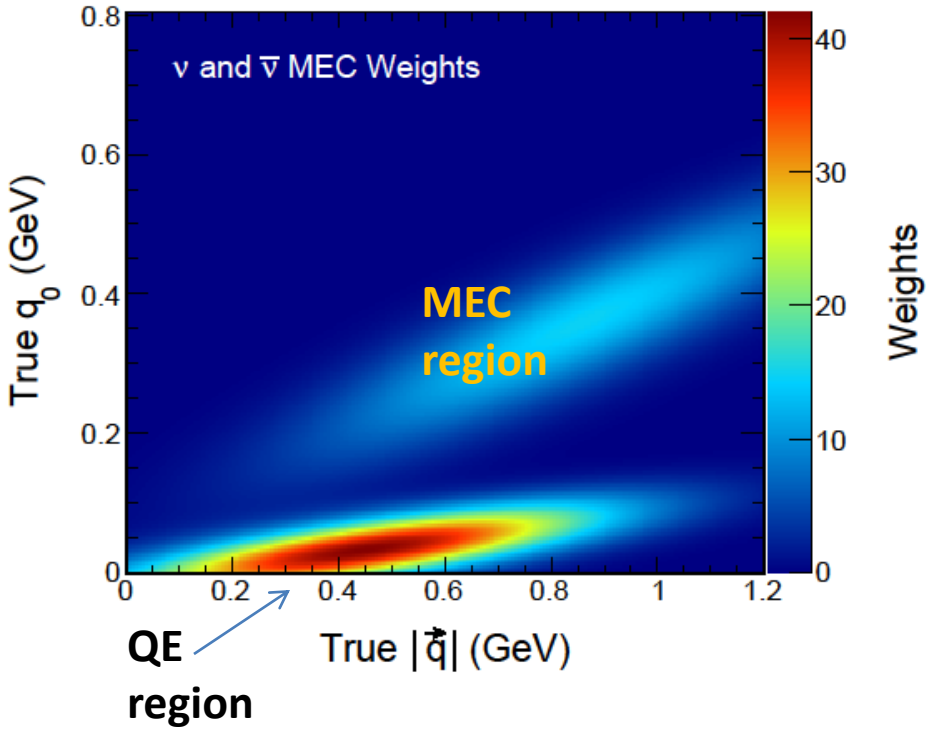
New RES+DIS tune

- GENIE 3.2.0 includes a new RES+DIS tune that is more comprehensive and fully replaces the existing 02_11a tune from 3.0.6. arXiv:2104.09179



Learning from our data: MEC weights

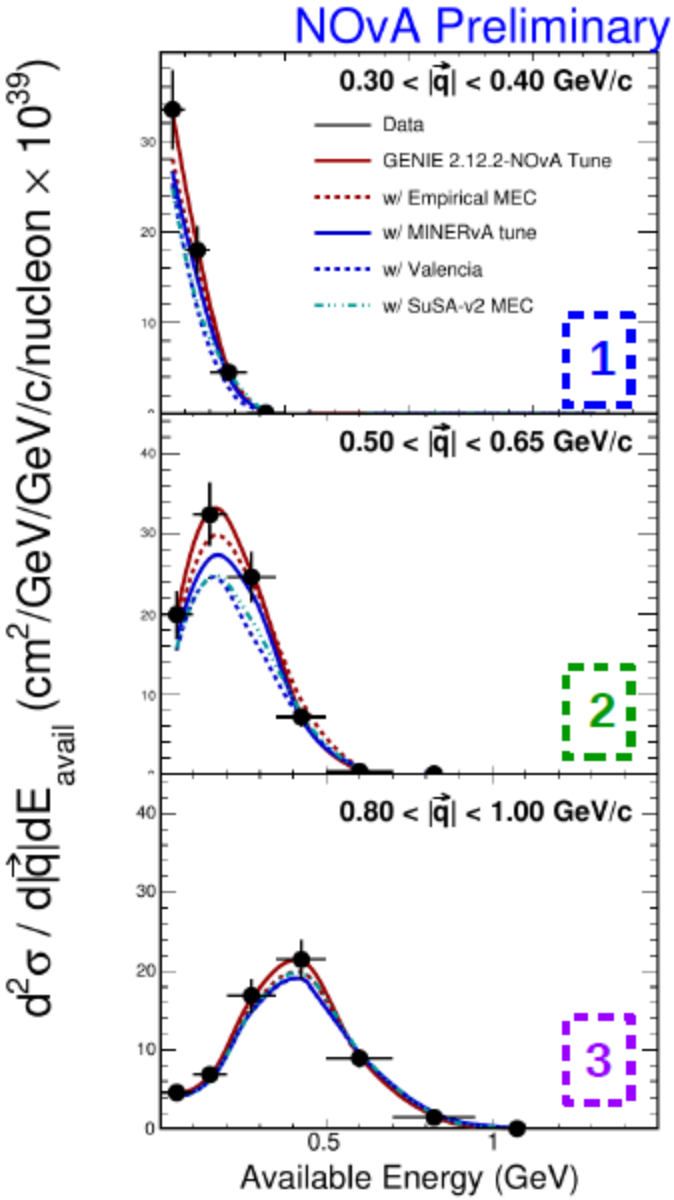
- Our MEC tune absorbs other model deficiencies; what might we be missing because of this?
- MEC weights large in QE region; is MEC tune fixing a deficit in QE?
- SuSAv2 QE model new in GENIE 3.2.0; behaves the same?
- Is RPA too strong?

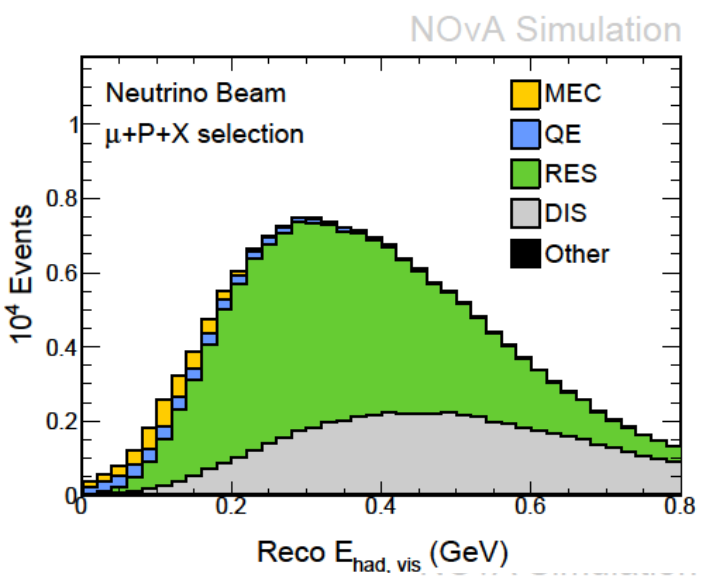


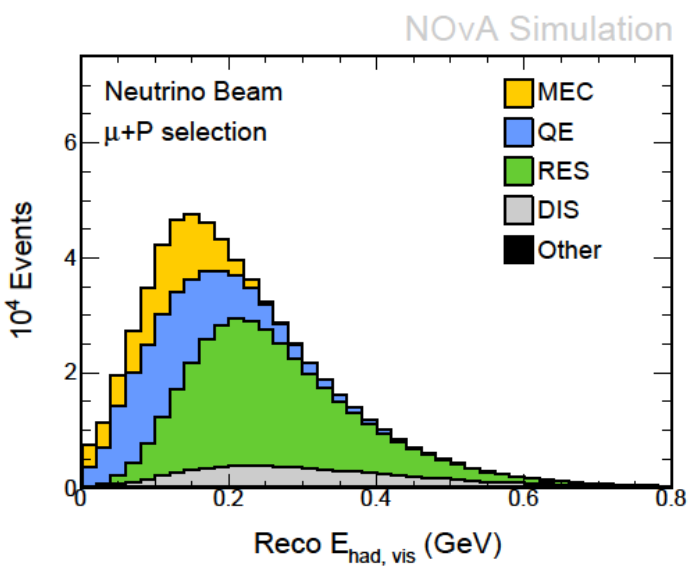
Pions

- Yesterday's NOvA result showed inconsistencies with ND data in pion-rich regions
- We want to explore this more fully; idea is to split data into physics-motivated subsamples

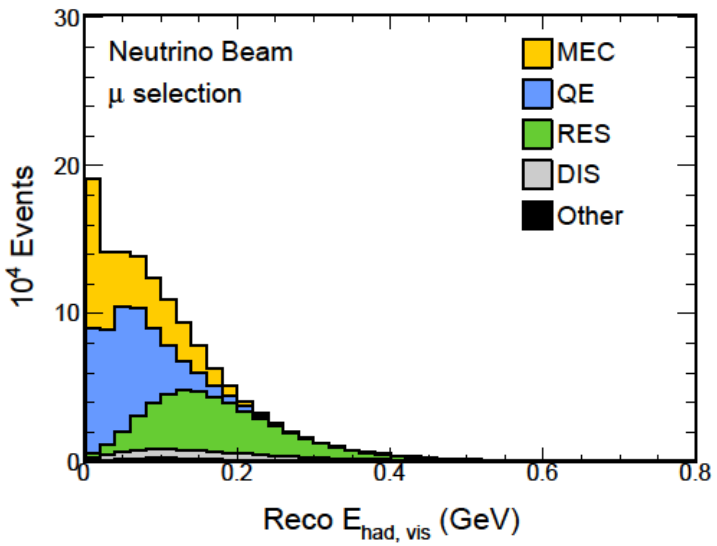
J. Wolcott

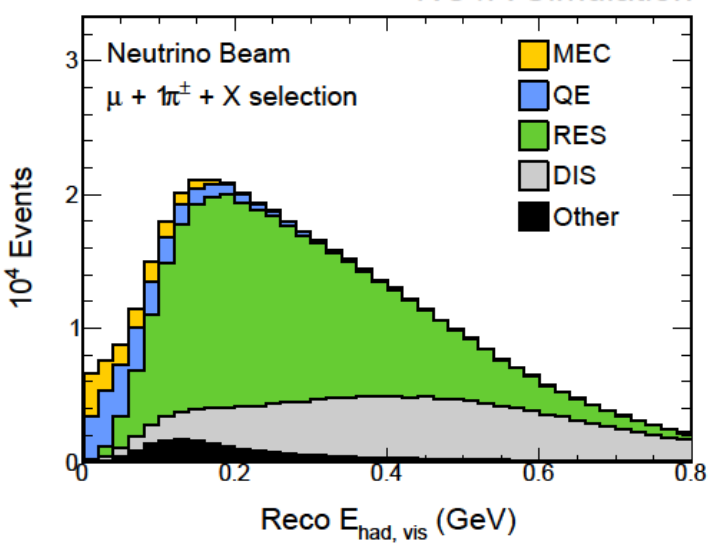






some of the subsamples, simulated





- This could be combined with a MEC fit that includes other cross-section uncertainties, so we might be able to separate what is MEC and what is from other model deficiencies

Conclusion

- Cross-section tuning necessary for long-baseline experiments as models aren't perfect
- Each experiment has different needs and approaches
- NOvA uses GENIE and has to strongly alter FSI and MEC models to agree with ND data
- Final result well within uncertainties, but further improvements are desired

Thanks