Neutrino Scattering - What We Know and What We Know We Don't Know!

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May 1, 2024
ICTS Understanding The Universe with Neutrinos Summer School

Please Note…

- I sincerely apologize that I cannot be there in person to meet and talk with you all!
- Since this is a school:
  - I have some questions throughout my slides that I would like you to answer afterward.
  - Please send me at least 1 follow-up question after each lecture. I will answer at least 1 question from each of you and post them in Slack (#flux-and-xsec-exp).
  - You may send me questions either via email (jpaley@fnal.gov) or Slack (@Jon Paley)

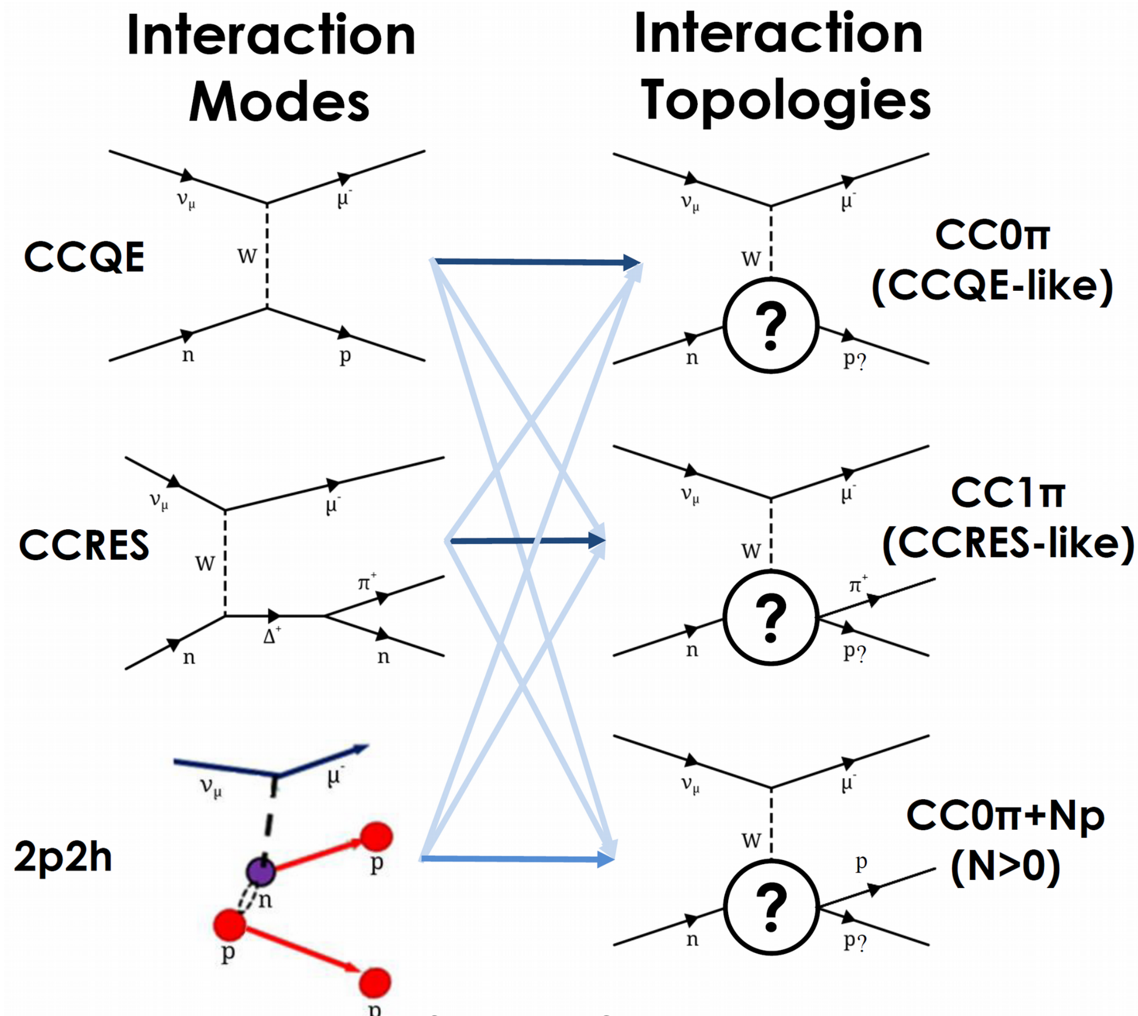
Outline

- Review of [some of] the experiments
- Review of [some of] the measurements:
  - 0π and the 2p2h saga
  - Exploring the impact of final-state interactions
  - Pion production
  - Inclusive measurements
  - Electron-neutrino measurements
- What we need to put it all together, and a look to the future

A Reminder…

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} P_j)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$

- Most neutrino cross sections are reported based on their final-state topology, eg:
  - CC inclusive (all interactions)
  - CC 0π (mostly CC QE + 2p2h)
  - CC 1π (mostly CC Res)
  - CC Nπ (mostly higher resonances + SIS/DIS)



Graphic by S. Dolan

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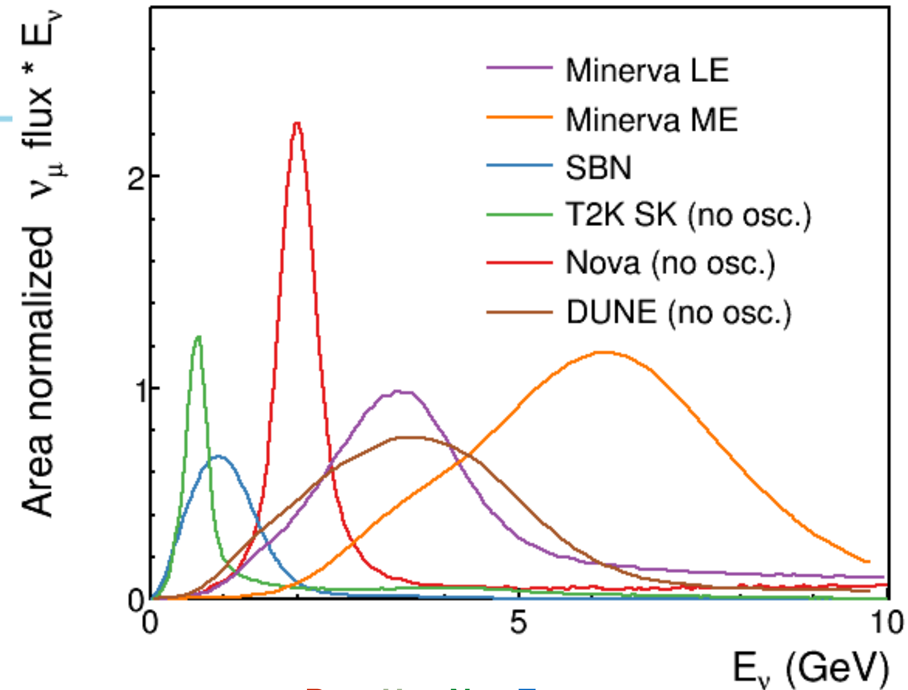
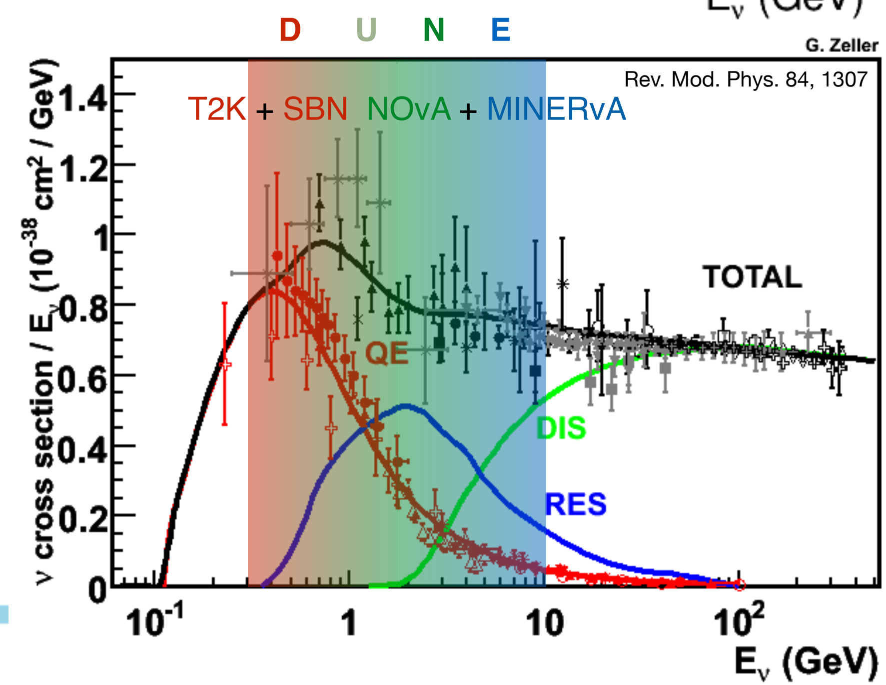
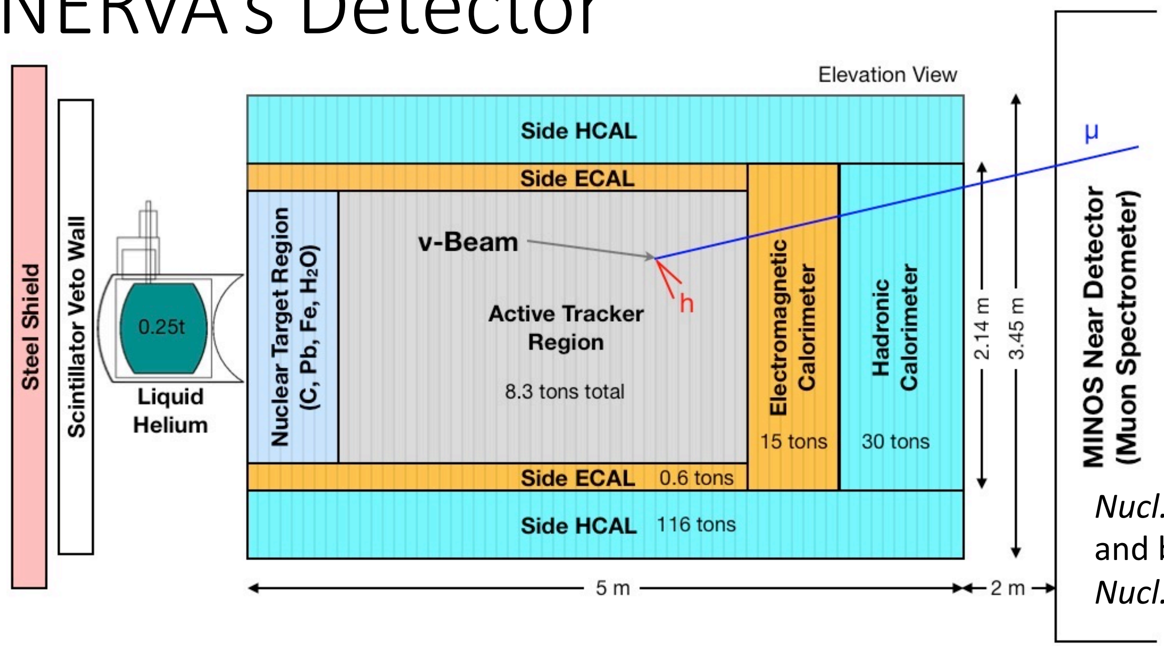
- The experiments making cross section measurements have different sensitivities (levels) of the topologies. In particular, T2K and SBN are dominated by QE and 2p2h interactions.





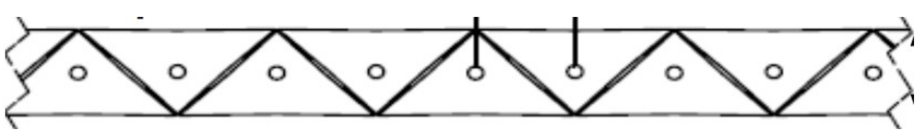
The Experiments and Their Detectors

MINERvA's Detector



Nucl.Instrum.Meth.A 743 (2014) 130 and beam test *Nucl.Instrum.Meth.A* 789 (2015) 28

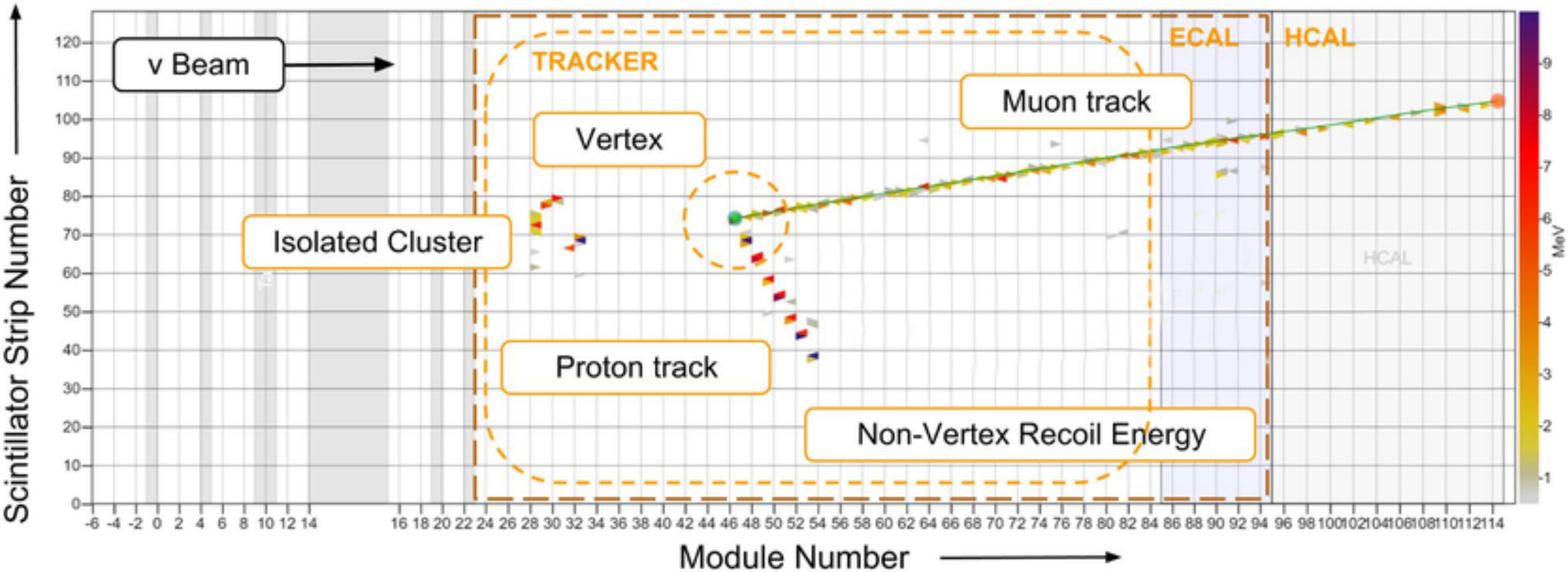
17mm



Three views:
X: Vertical
U,V: ± 60

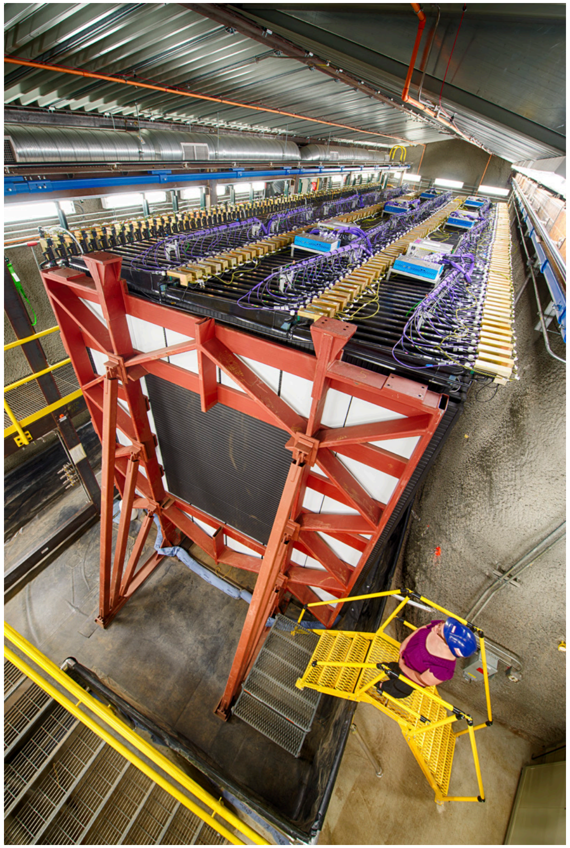
Spatial resolution ~3mm
Timing resolution ~3ns

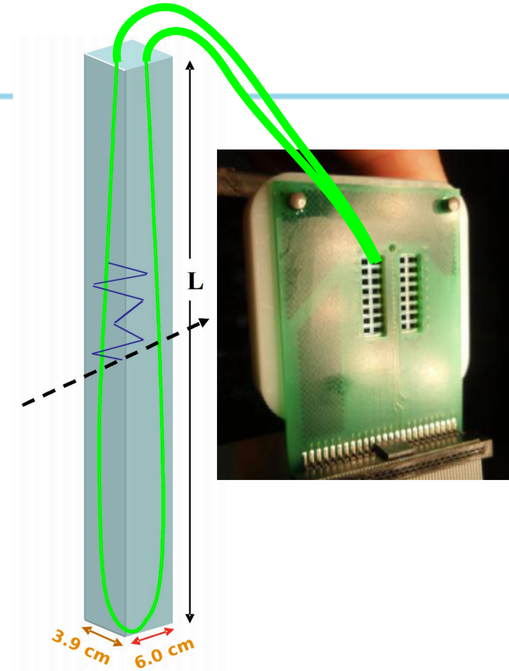
MINERvA



- Particle id mostly via dE/dx in the active tracker region.
- Limited angular acceptance since muons must enter the downstream MINOS near detector.
- A variety of nuclear targets upstream enables cross-section A-dependence.

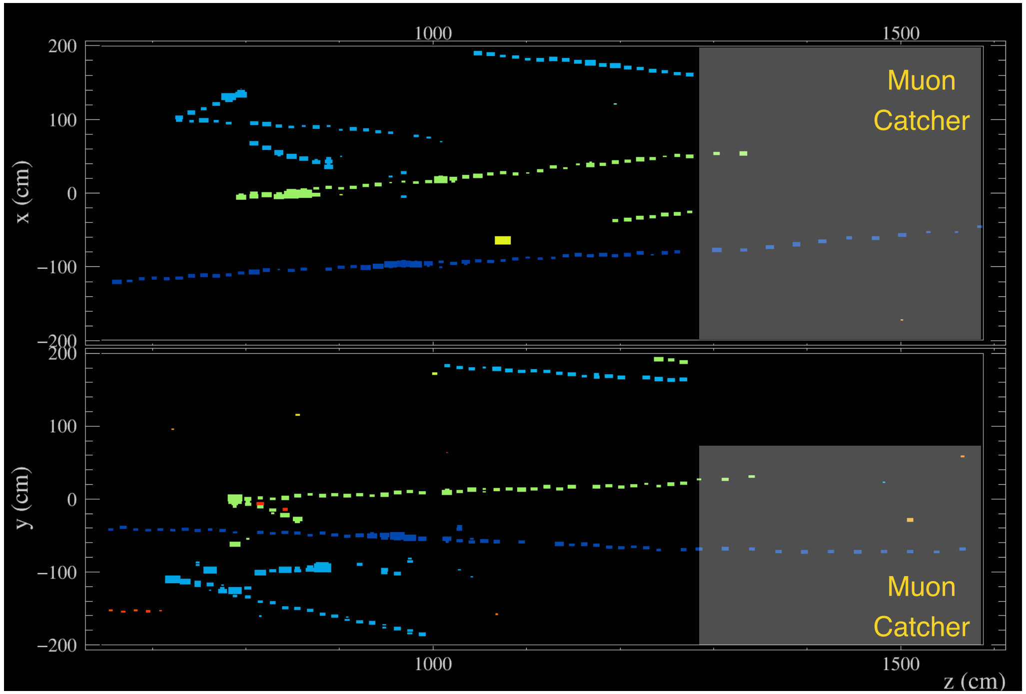
NOvA Near Detector

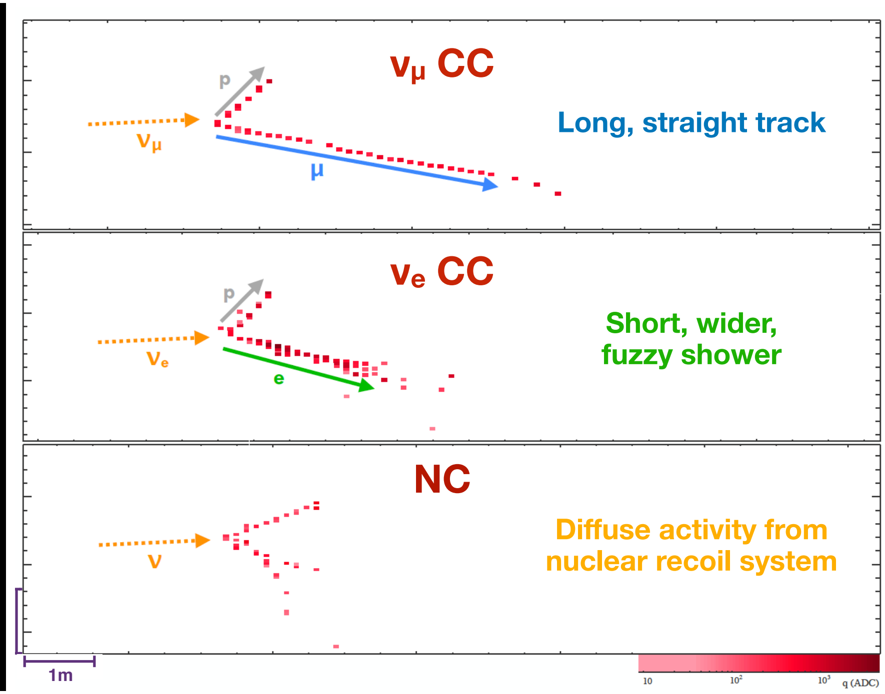




- 300t tracking calorimeter, constructed from extruded PVC cells filled with liquid scintillator.
- Scintillation light captured and routed to APDs via WLS fibers.
- 0.07 X_0 per layer
- **77% CH_2, 16% chlorine, 6% TiO_2 by mass**

NOvA Near Detector

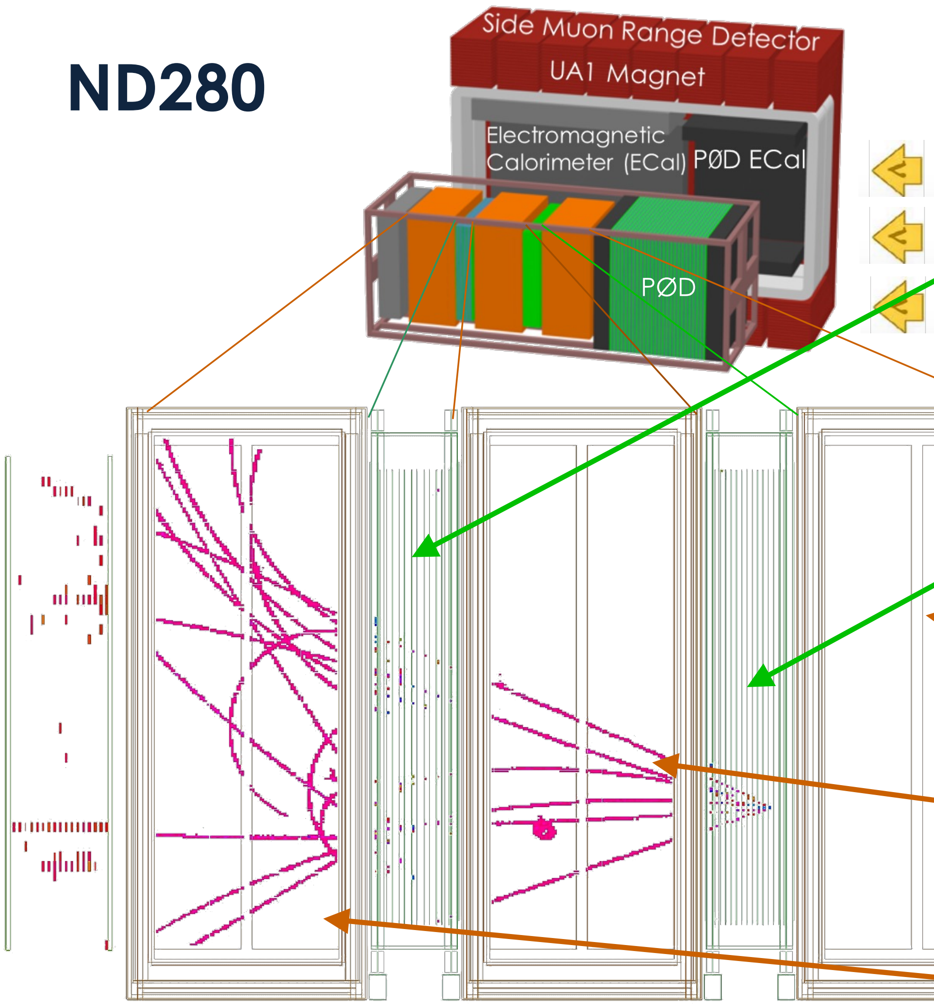




- Muon catcher (steel + NOvA cell at the downstream end ranges out ~2 GeV muons.
- 5 ns hit-level timing resolution used to separate the many neutrino interactions per 10 us spill.
- NOvA is an oscillation experiment and the detectors and reconstruction are designed to optimize muon and EM-shower measurements. So, very good at identifying and measuring the energies of muons, electrons and π0s in the final state, improvements to reconstruction of other particles are underway.

T2K ND280

ND280



On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

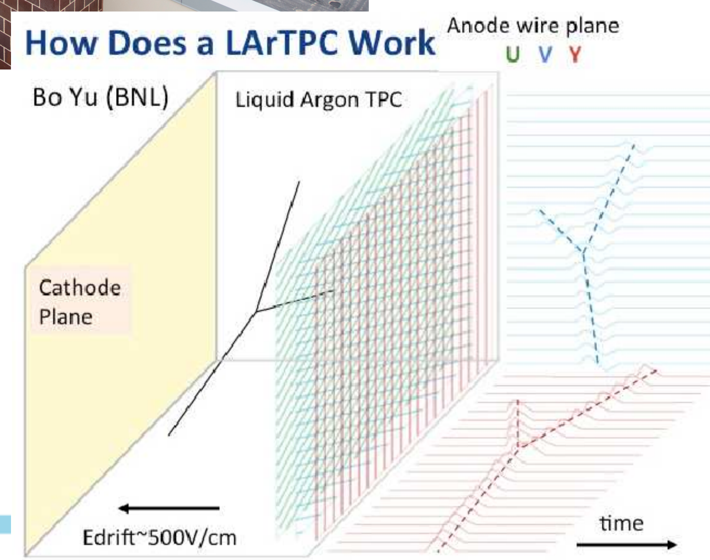
Fine-Grained Detectors (FGD 1 & 2):

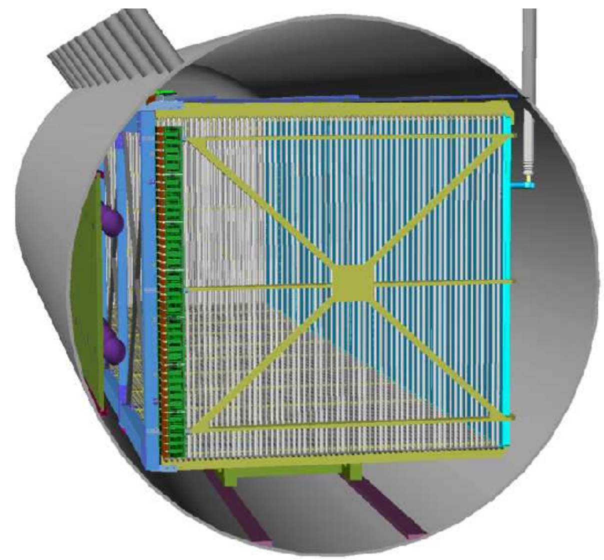
- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

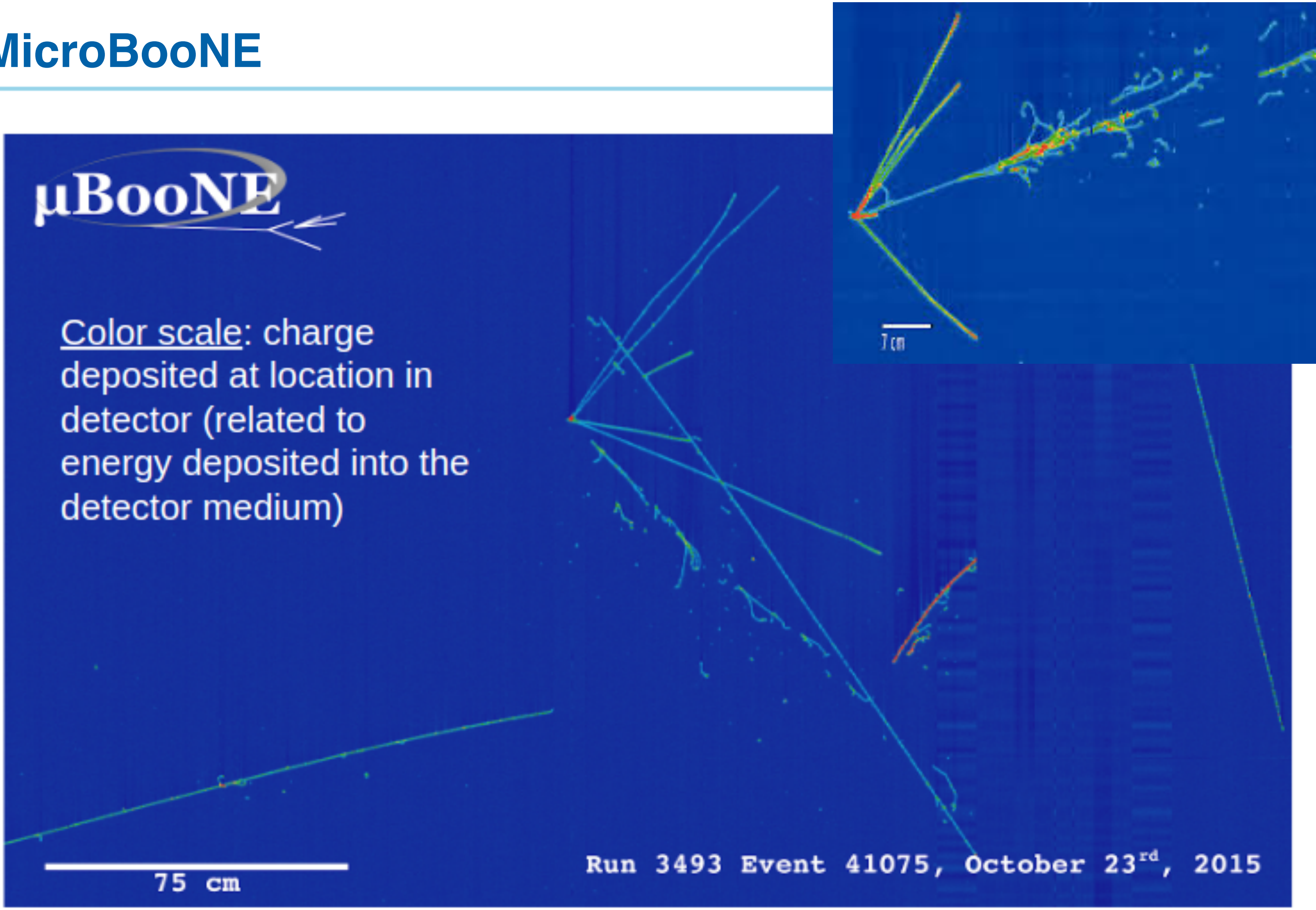
- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

MicroBooNE


How Does a LArTPC Work
Anode wire plane
U V Y
Bo Yu (BNL)
Liquid Argon TPC
Cathode
Plane
Edrift~500V/cm
time



MicroBooNE



Color scale: charge deposited at location in detector (related to energy deposited into the detector medium)

A Brief Survey of Some Measurements And Their Comparisons to Event Generator Predictions

Note: the news is not so great… in general, generator predictions are pretty far off from our measurements.

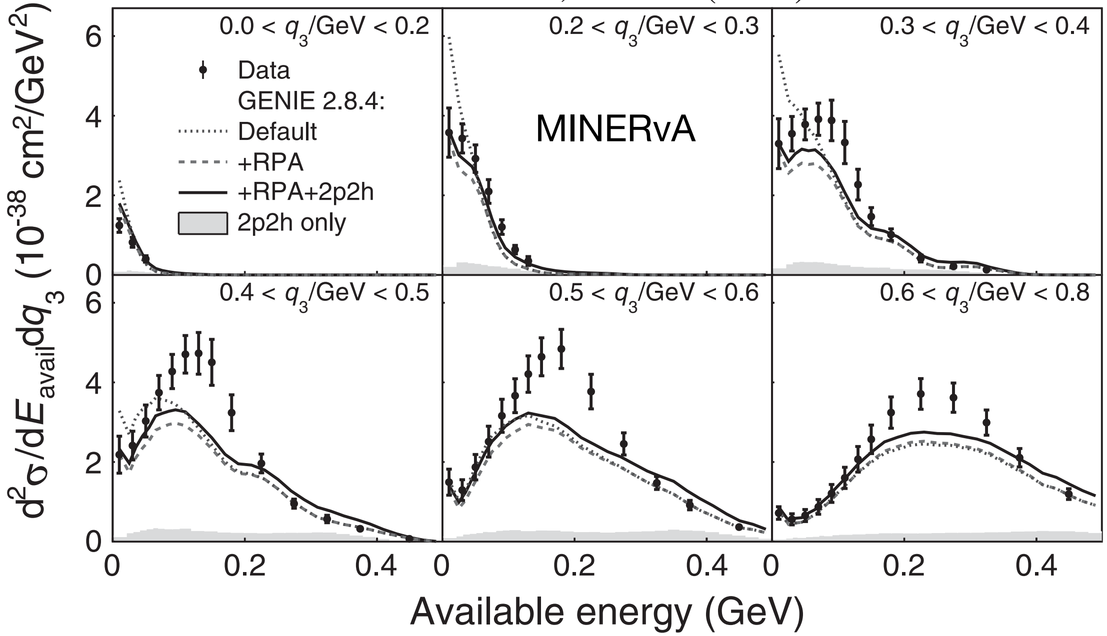
A Brief Survey of Some Measurements And Their Comparisons to Event Generator Predictions

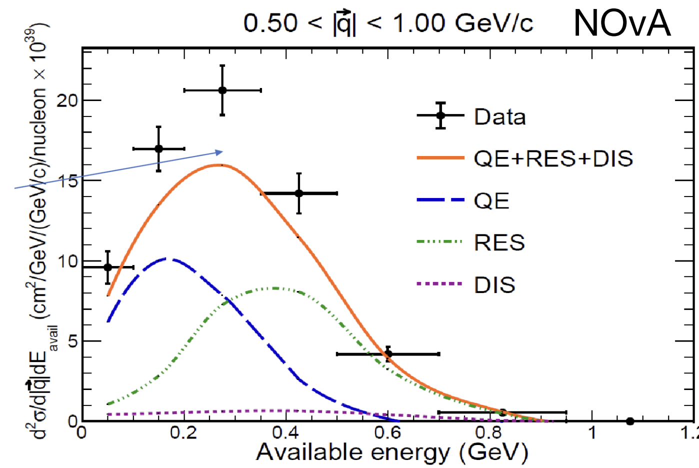
Note 2: this is a huge topic, and I simply can't cover everything in this one lecture. If you are interested in learning more, I suggest:

- **check out/get involved in NuSTEC (nustec.fnal.gov)**
- **Join the NuSTEC-new email list (see https://nustec.fnal.gov/nustec-news/ for instructions)**
- **Read the NuSTEC 2017 White Paper (http://inspirehep.net/record/1604295)**
- **Read the new NuSTEC (2024?) White Paper when it comes out**
- **Checkout the talks in the most recent NuInt Workshop**

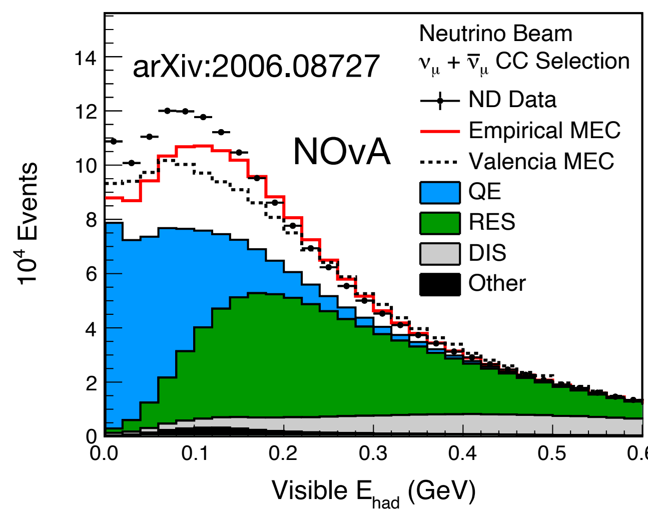
The 2p2h Saga…

PRL **116**, 071802 (2016)

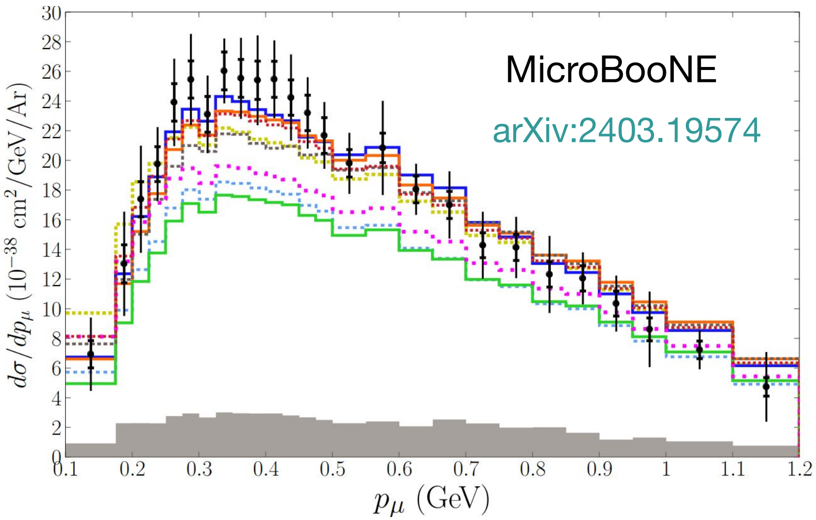


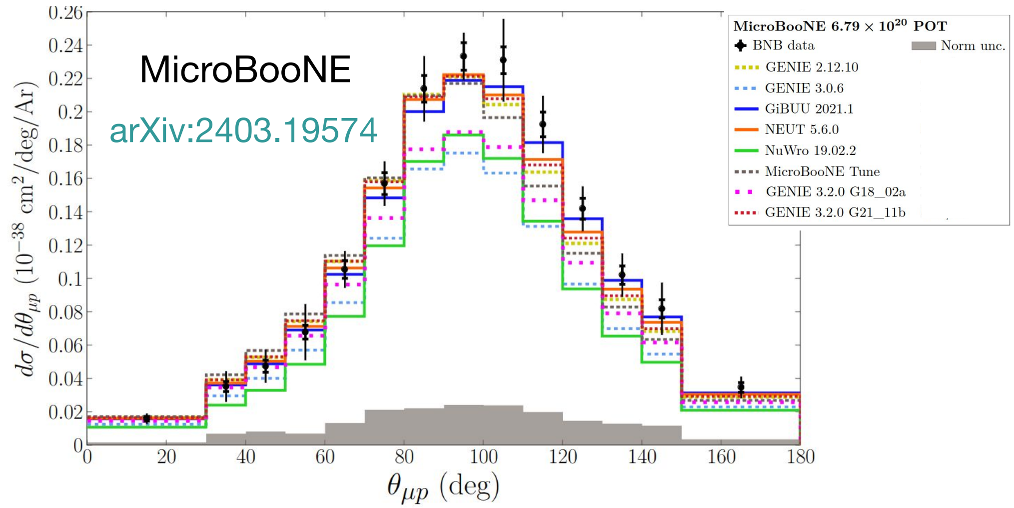


- In 2016, MINERvA published results showing a measured cross section much larger than was predicted in the their event generator at low momentum transfer.
- The excess of events appears at momenta transfer consistent with 2p2h interactions (a process already known from electron scattering experiments).
- NOvA showed a similar discrepancy in their data soon after. Studies show that no theory model is able to "fill in this gap".

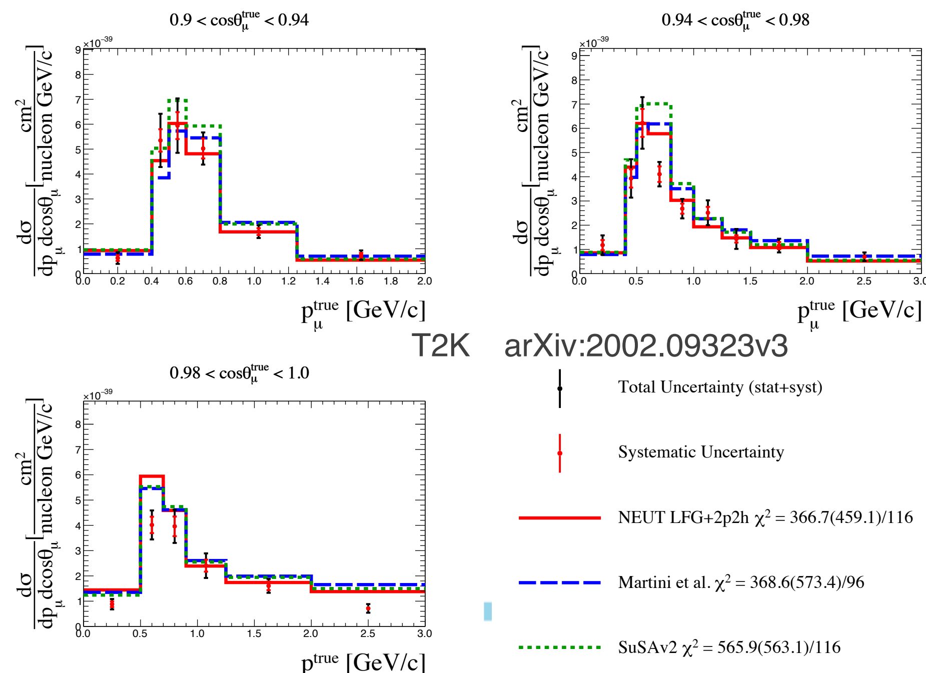


The 2p2h Saga…

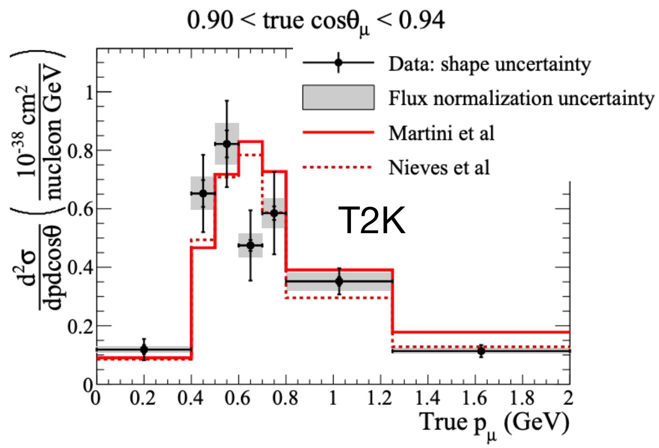


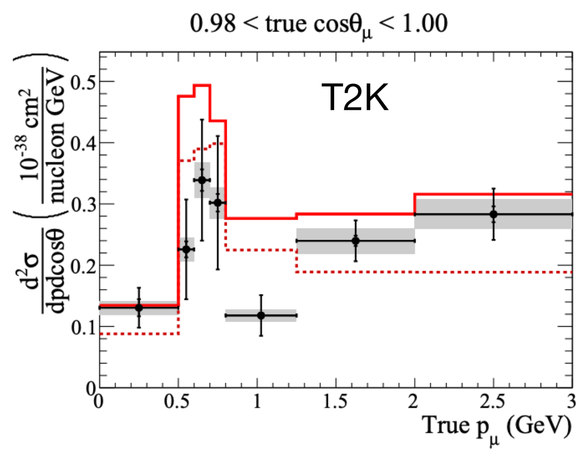


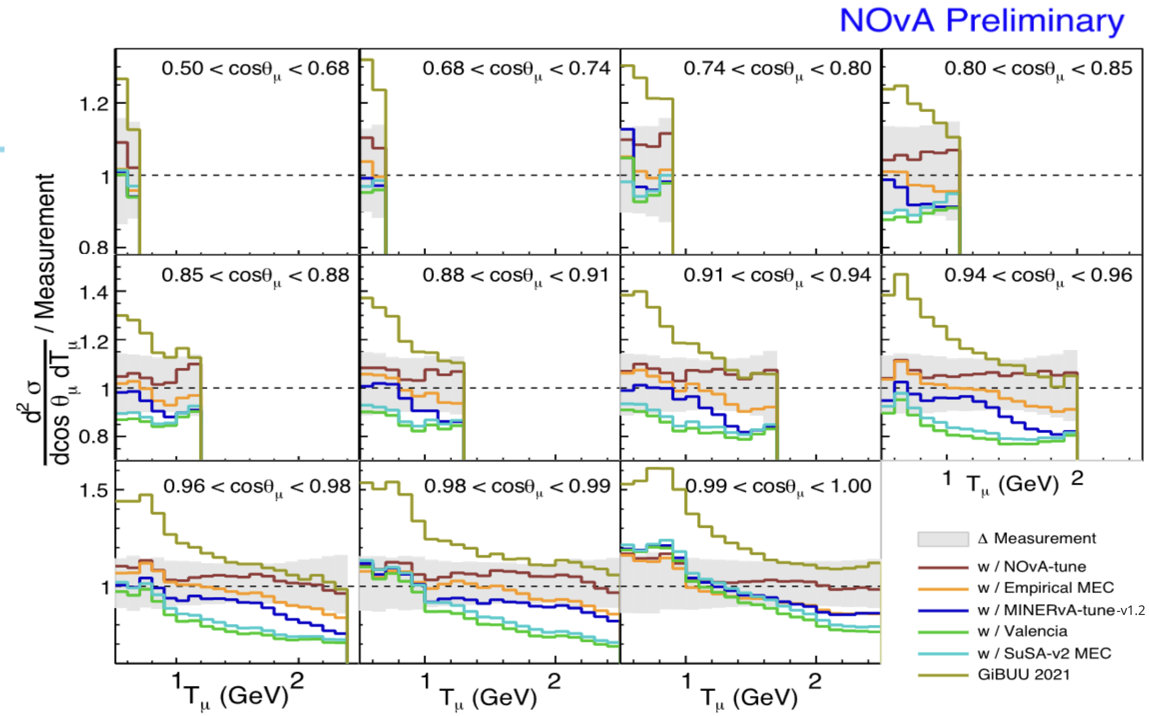
- And yet the models seem to work pretty well for both MicroBooNE and T2K.
  - This may not appear to be the case looking at the MicroBooNE plots above, but the chi2 comparisons between the data and predictions are all very reasonable.
- **So either there is an unaccounted neutrino-energy dependence in 2p2h interactions, or there is something else that we are not modeling at higher energies.**

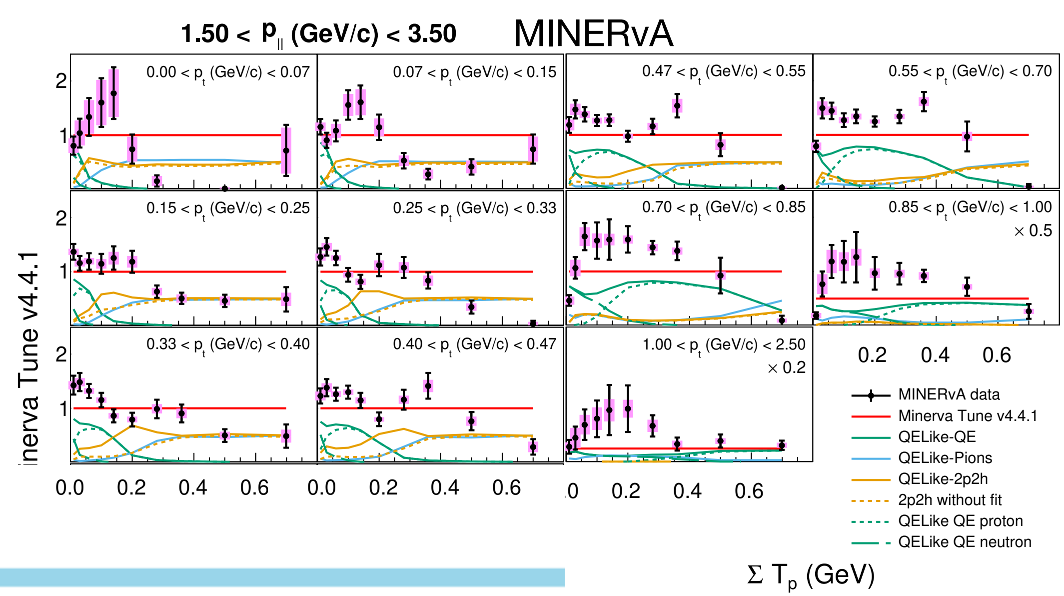


CC 0π Measurements



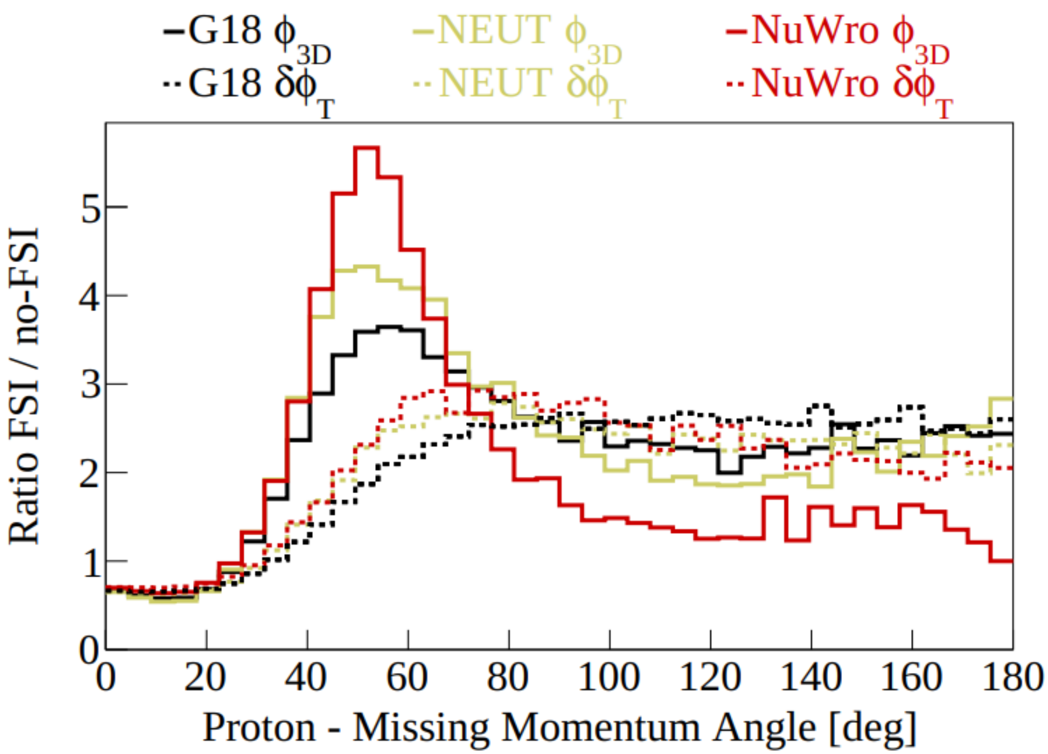


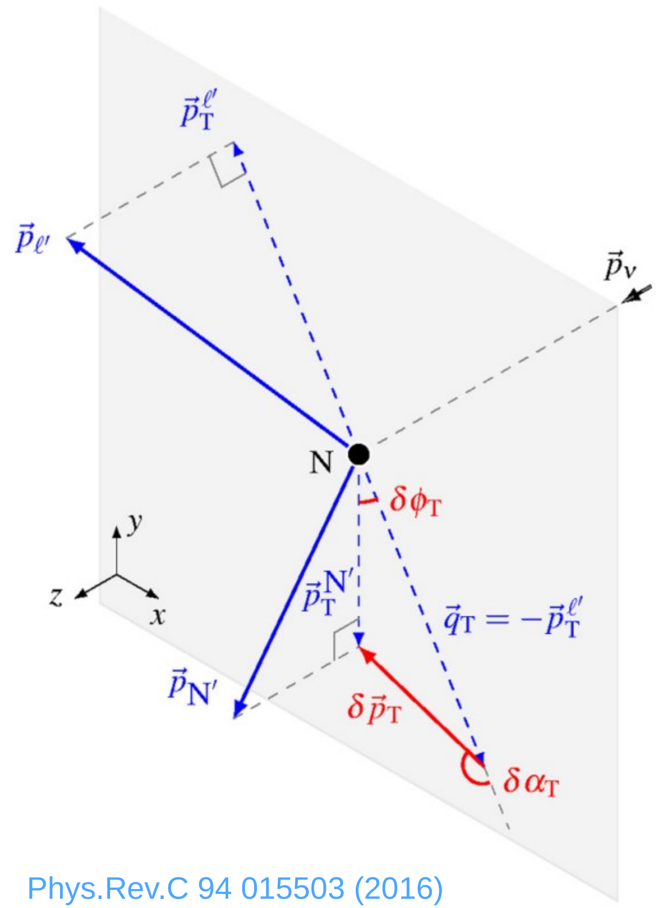




CC 0π Measurements - Transverse Kinematic Imbalance

- The idea: look for imbalance in the transverse momenta of the final-state particles.
- These observables are sensitive to effects of final state kinematics!





Phys.Rev.C 94 015503 (2016)

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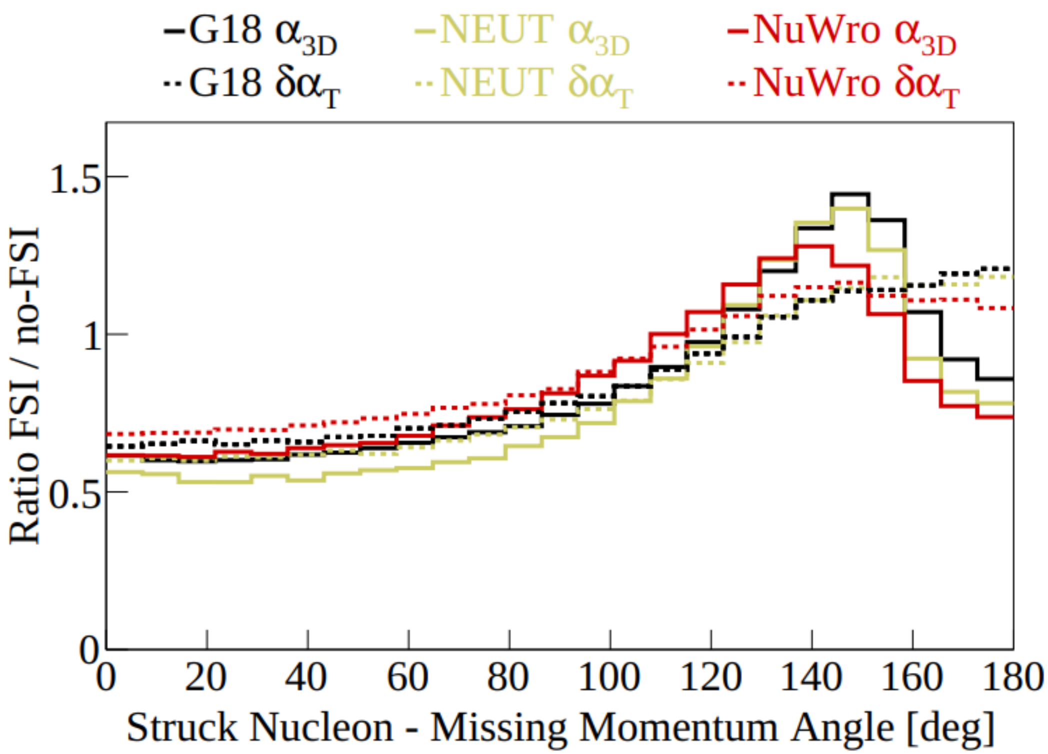

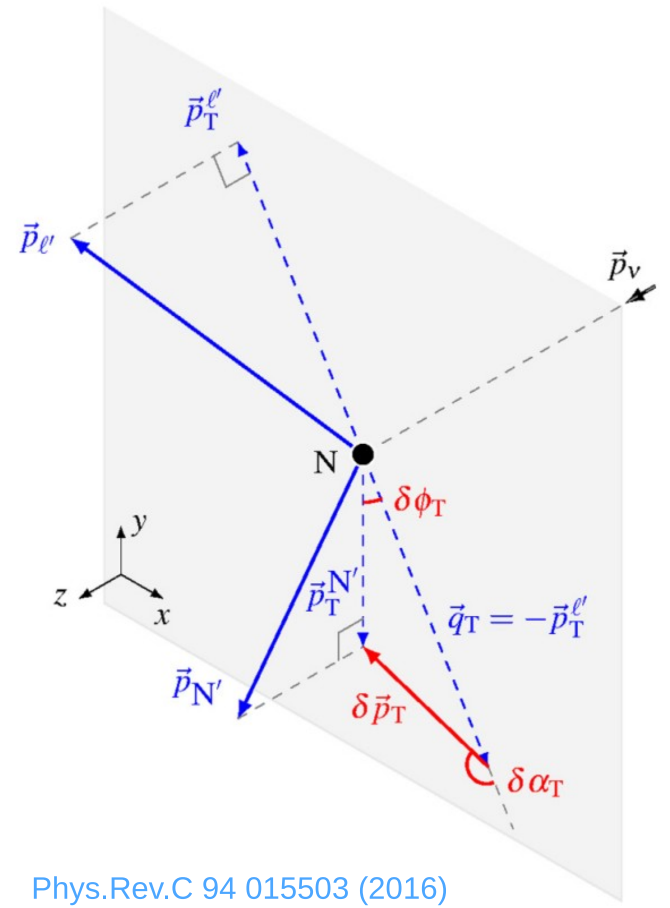

Phys.Rev.C 94 015503 (2016)

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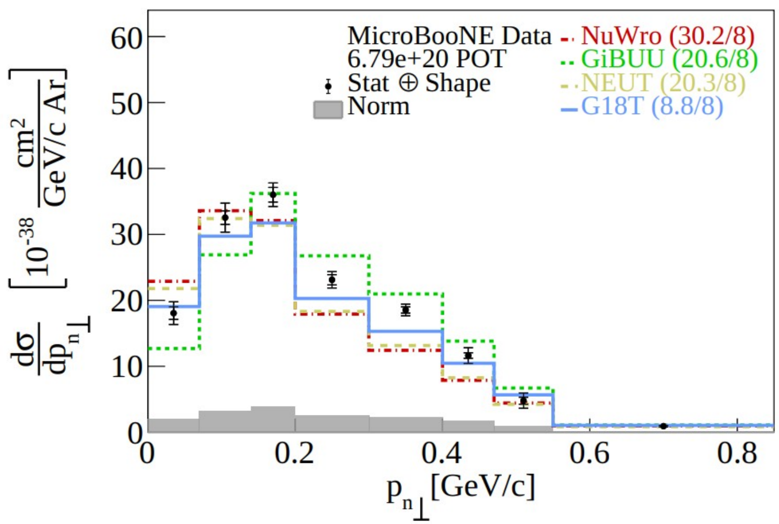
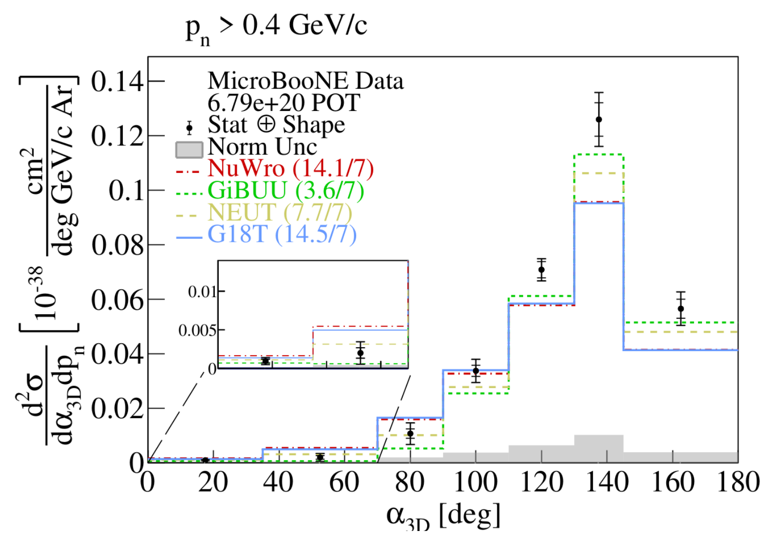
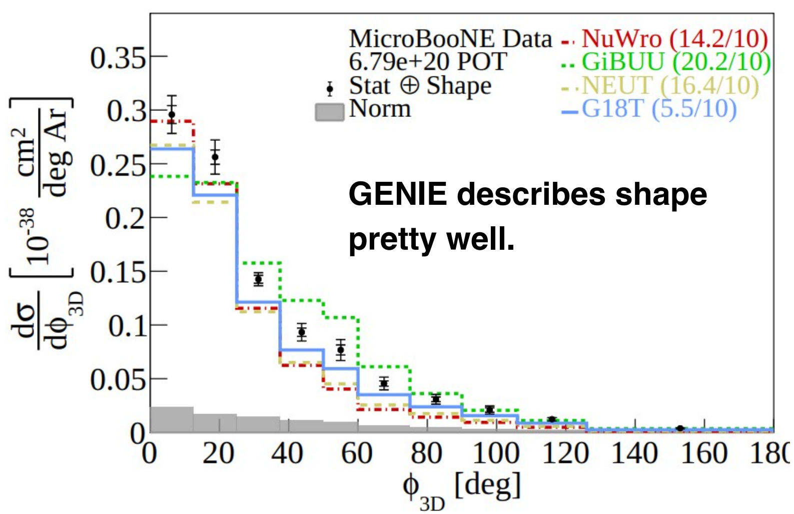
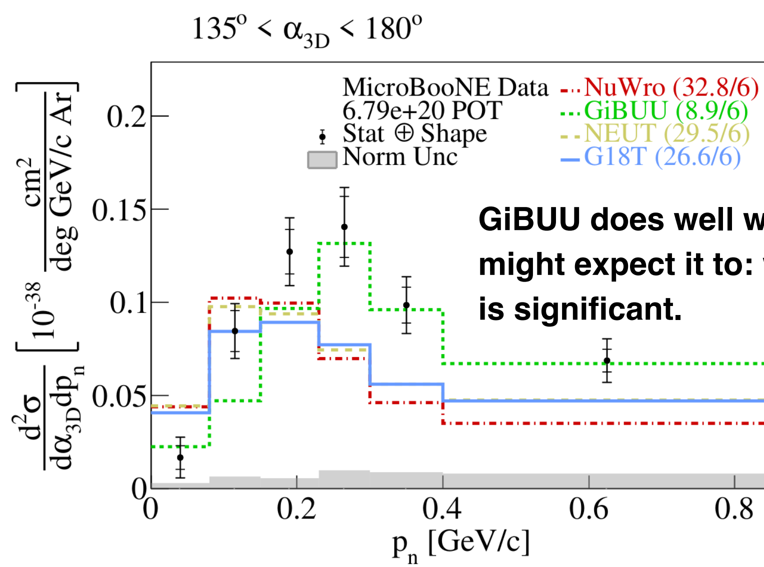






GENIE describes shape pretty well.



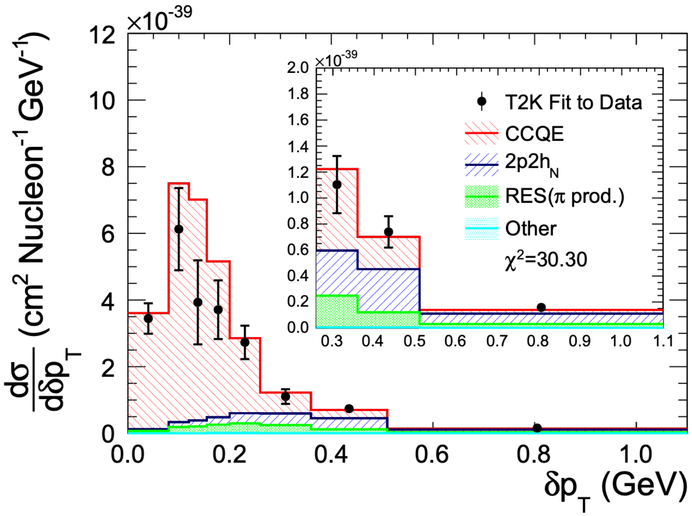
GiBUU does well where we might expect it to: where FSI is significant.

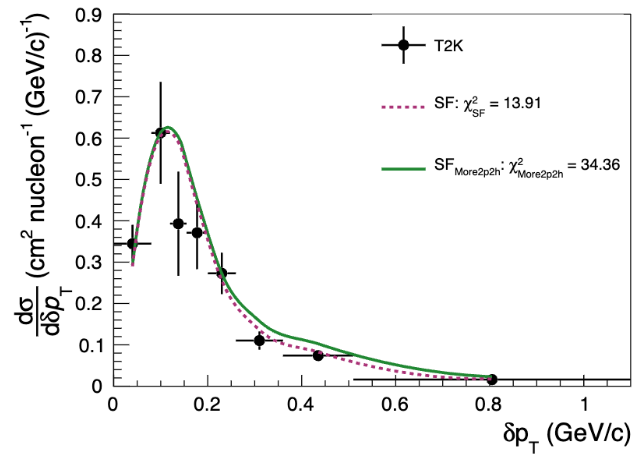
CC 0π Measurements - Transverse Kinematic Imbalance

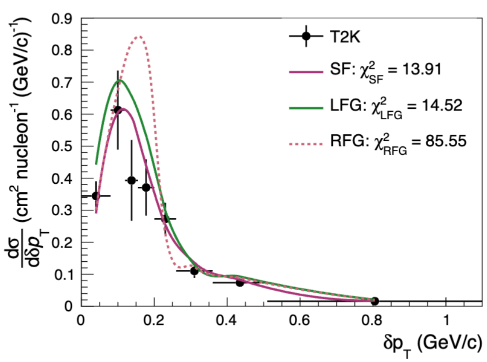
T2K Measuring muon+proton kinematics

Youthful optimism

- Measuring muon-proton correlations (2018) Phys. Rev. D **98**, 032003



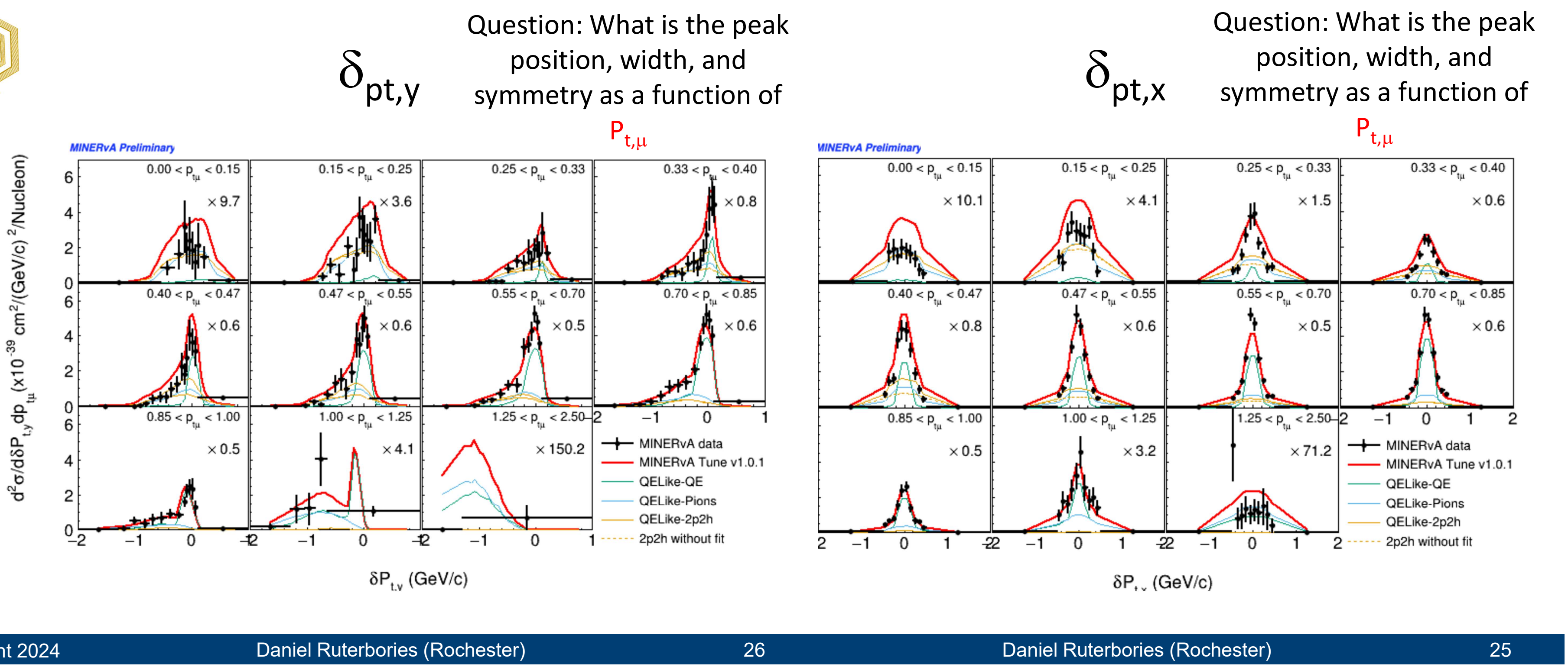




What we've learnt

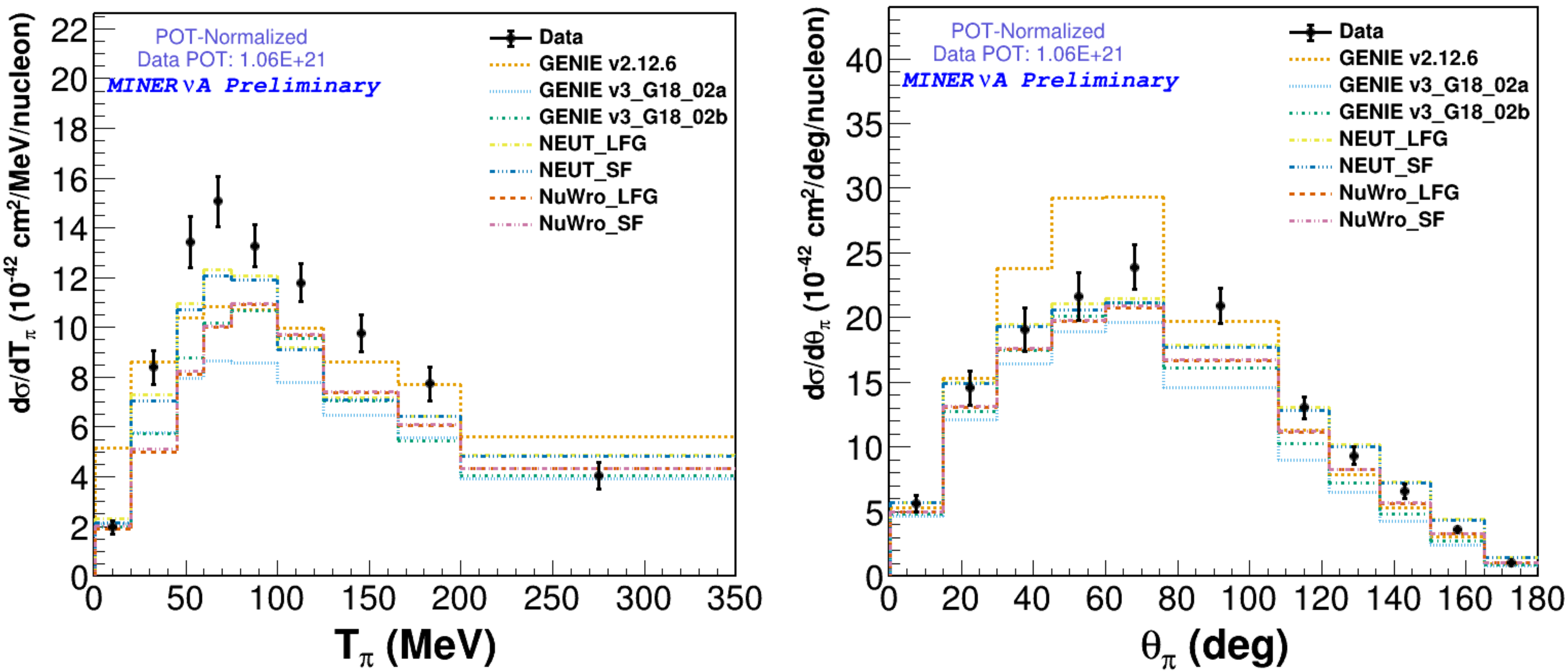
- No model quantitatively describes measurements
- RFG models clearly rejected
- Robust estimation of QE vs non-QE in CC0π+Np
- Clear requirement for 2p2h+π abs not much scope to alter one without changing the other

CC 0π Measurements - Transverse Kinematic Imbalance



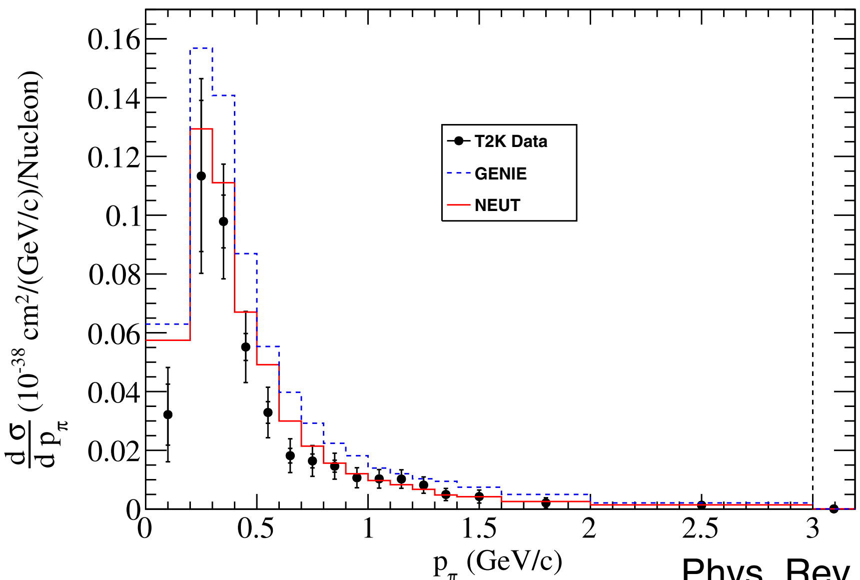
MINERvA: tuned cross section model (to their own data, but not using these observables) does ok in some regions of phase space, but does not do so well in others.

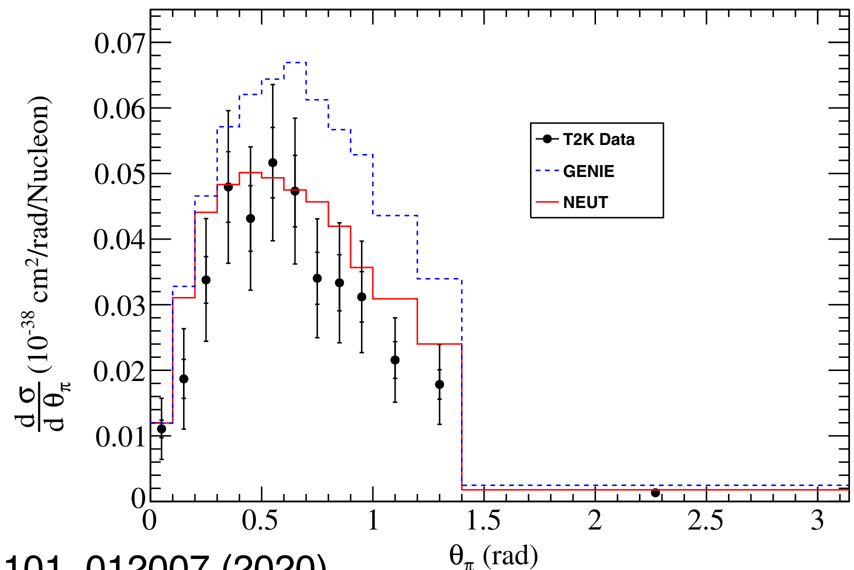
CC 1π Measurements



- Angular distribution of pions seems to be relatively well modeled. The energy distribution is peaked at lower energies than most models.

CC 1π Measurements

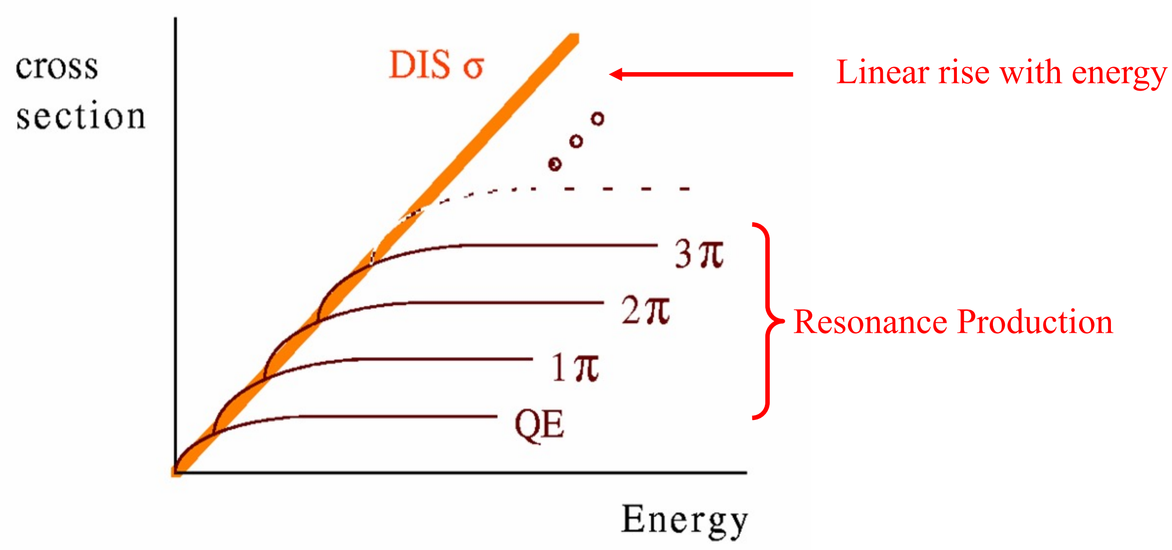


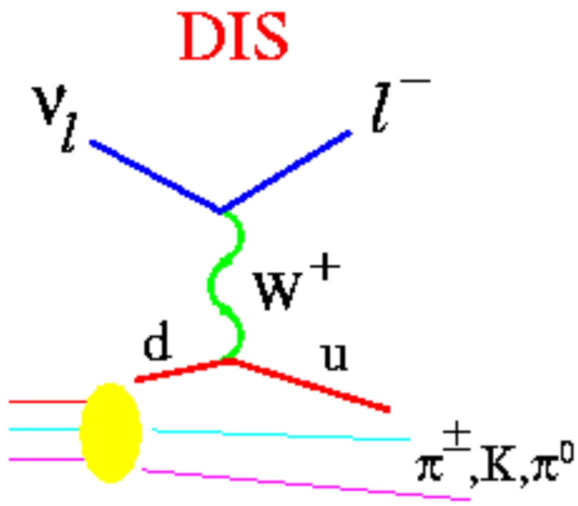


Phys. Rev. D 101, 012007 (2020)

- NEUT seems to be doing a good job predicting the pion kinematics.
- The GENIE cross section seems a bit high, and predicts higher momenta and larger angles than the data.

CC Nπ Measurements

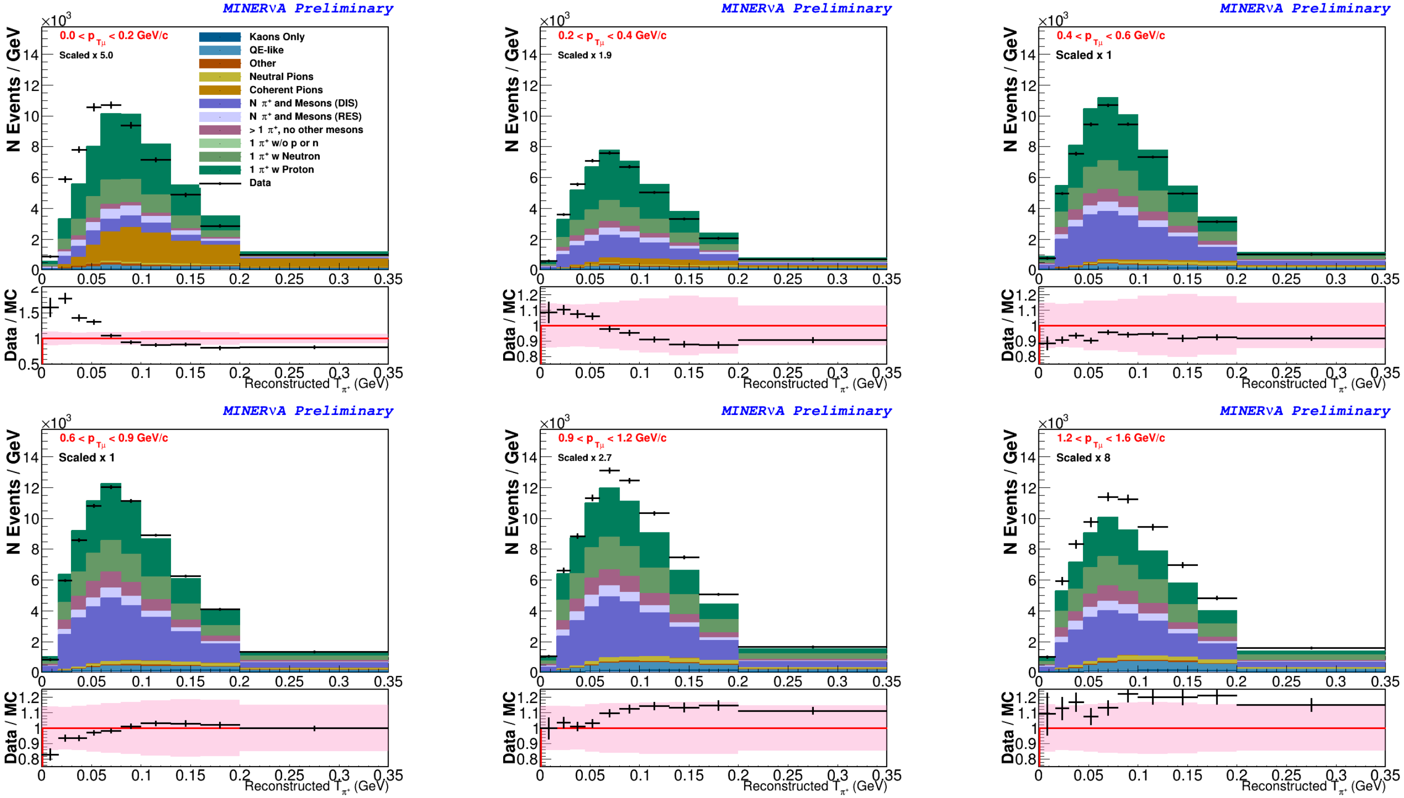




- As we go to higher energies, shallow- and deep-inelastic scattering can produce more than one pion in the final state.
- Most interactions in NOvA and DUNE involve pion production.
- The energy to create the pion needs to be accounted for when reconstructing the neutrino energy - important for oscillation measurements!
- Pions are susceptible to FSI

CC Nπ Measurements

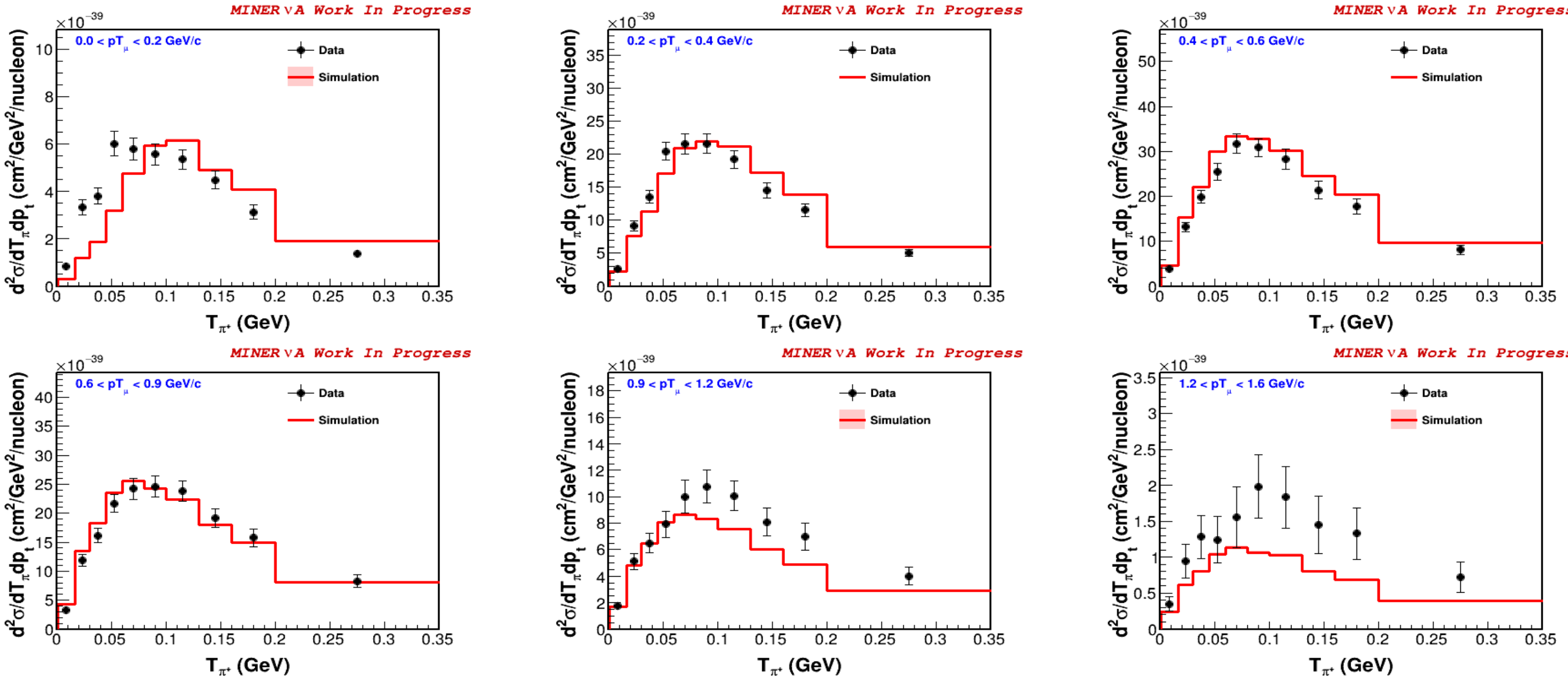
CC≥1π^+ Events versus T_π and $p_{t\mu}$ with tune



- Notice many contributing processes at each pion momentum
- Statistical error only on data points

CC Nπ Measurements

CC≥1π^+ Cross Section vs. T_π and $p_{t\mu}$

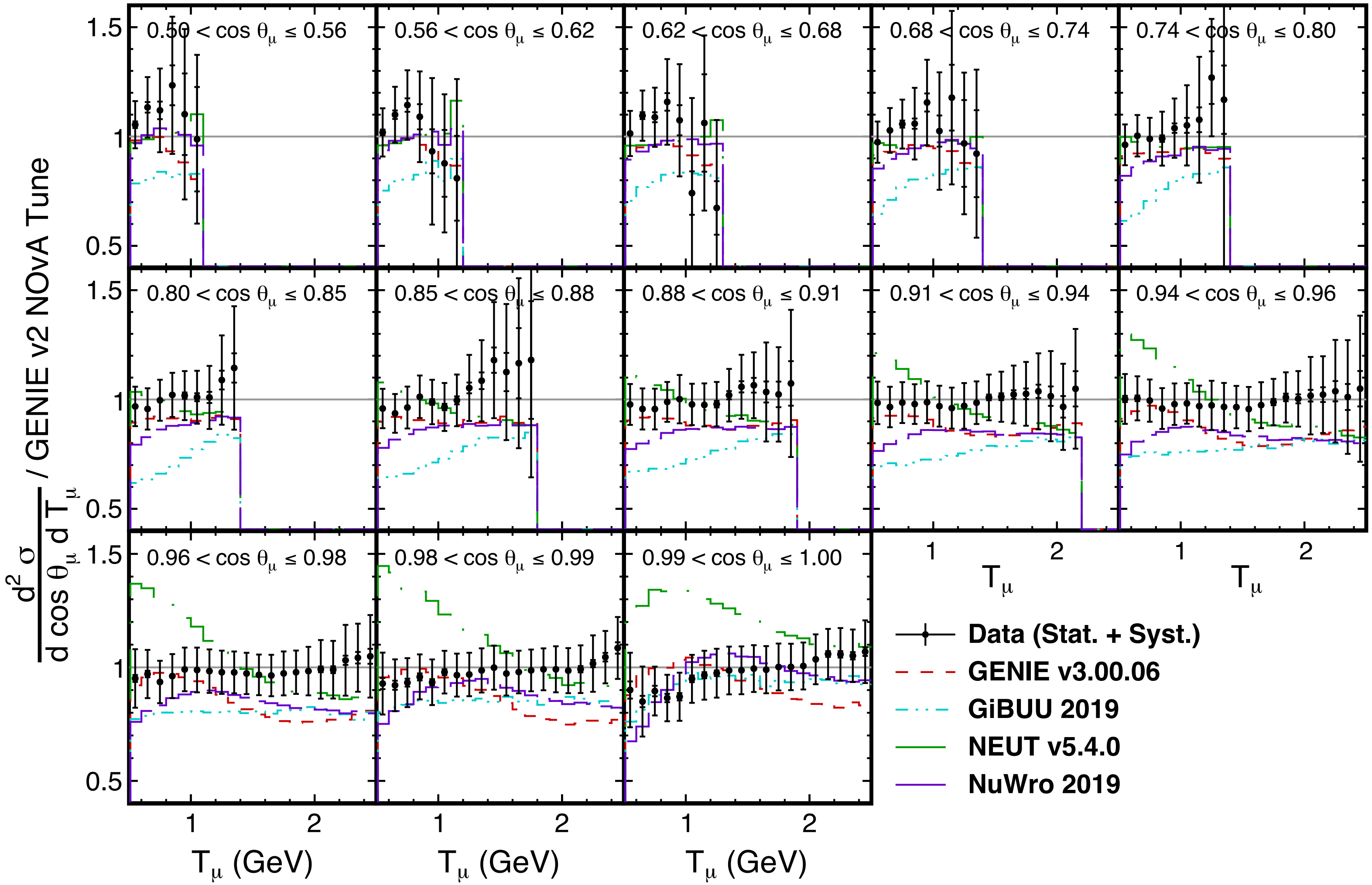


- Can look at transition from resonance to SIS to DIS

Notice excess at low p_t and high p_t, intermediate p_t shows better agreement with base model (MnvTunev4.3.1)

CC Inclusive Measurements

Phys. Rev. D 107, 052011 (2023)



$\bar{\nu}_\mu$ Charge Current Inclusive Measurement

GENIE MC/Data Ratios

- None of the theory-based models fully reproduce our measurements
- SuSA-v2 model better reproduces data than Valencia for QE
- For MEC, Valencia and Susa-v2 are very similar and neither model matches the data

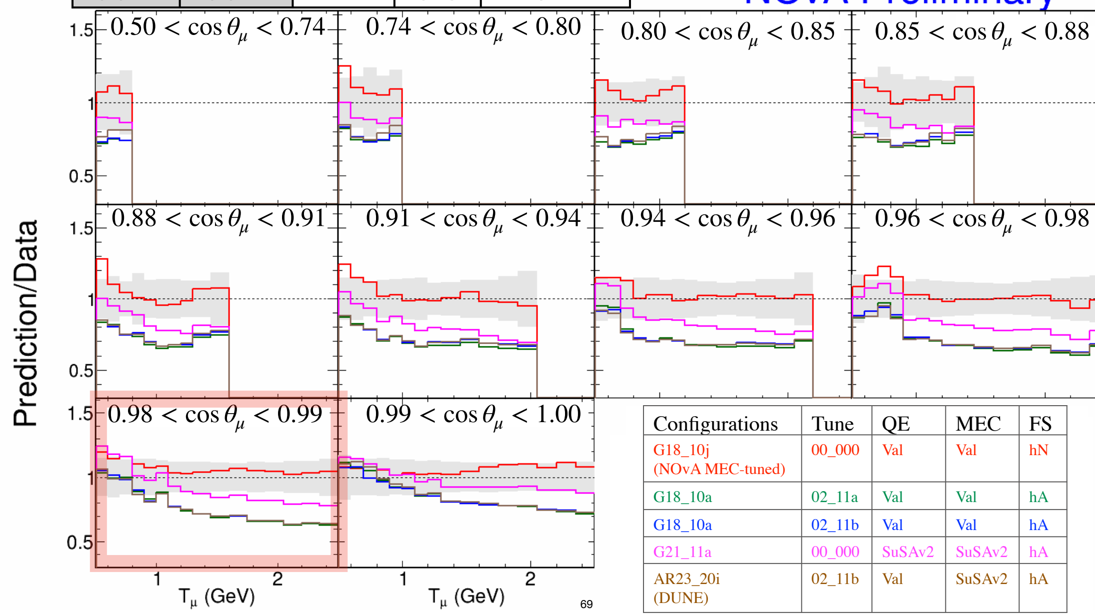
0 < E_{avail} < 100 MeV

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
59.4	35.4	4.4	0.6	0.2

Events: 48%

NOvA Preliminary



Configurations	Tune	QE	MEC	FS
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	hN
G18_10a	02_11a	Val	Val	hA
G18_10a	02_11b	Val	Val	hA
G21_11a	00_000	SuSAv2	SuSAv2	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	hA

CC Inclusive Measurements

$\bar{\nu}_\mu$ Charge Current Inclusive Measurement

GENIE MC/Data Ratios

100 MeV < E_{avail} < 300 MeV

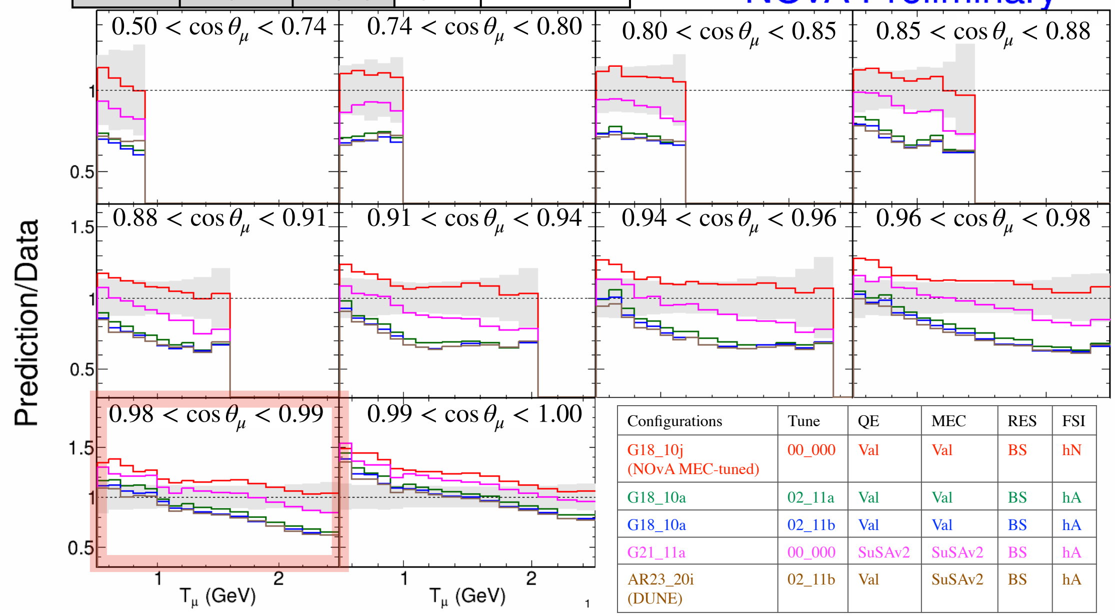
Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
21.4	18.2	48.0	8.4	4.1

Events: 22%

NOvA Preliminary

- Similar conclusions can be drawn in the 100-300 MeV E_{avail} bin as that 0-100 MeV bin wrt Data/MC ratios:
  - SuSA-v2 better describes QE physics
  - Both theory models poorly describe MEC



Configurations	Tune	QE	MEC	RES	FSI
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	BS	hN
G18_10a	02_11a	Val	Val	BS	hA
G18_10a	02_11b	Val	Val	BS	hA
G21_11a	00_000	SuSAv2	SuSAv2	BS	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	BS	hA

$\bar{\nu}_\mu$ Charge Current Inclusive Measurement

GENIE MC/Data Ratios

300 MeV < E_{avail} < 600 MeV

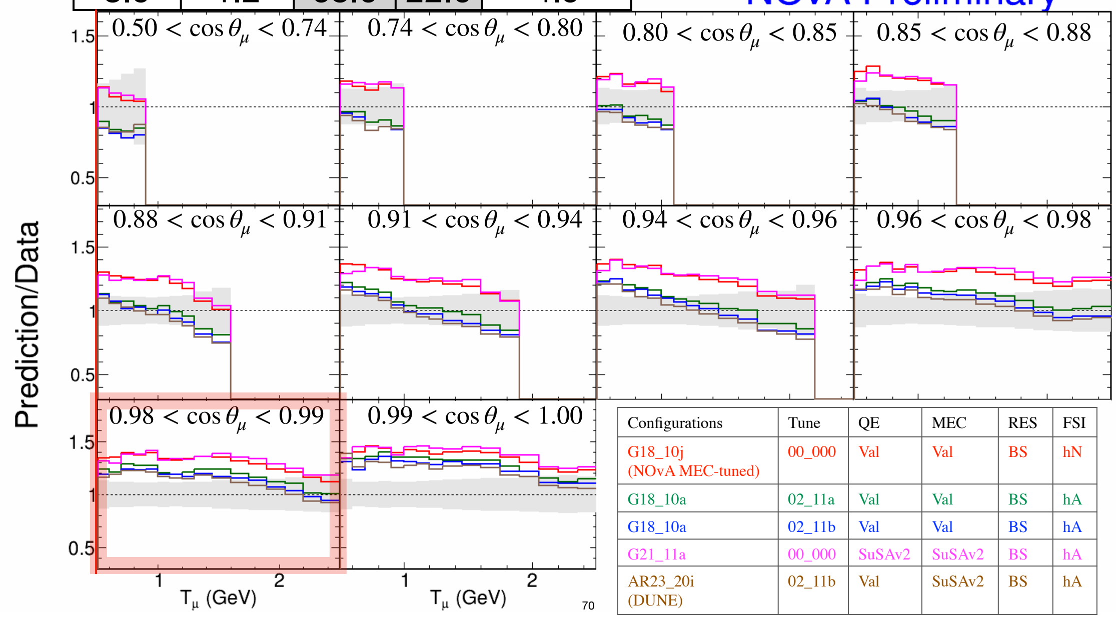
Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
3.9	1.2	68.0	22.0	4.9

Events: 14%

- Differences between the CMCs
  - GENIE tune 00_000 has no external data tune applied
  - 02_11a/b tunes adjust the model to match external single-nucleon data in modeling RES event
- We find that the 02_11 tunes to external data perform do perform better than the 00_0000 in this RES enhanced region

NOvA Preliminary



Configurations	Tune	QE	MEC	RES	FSI
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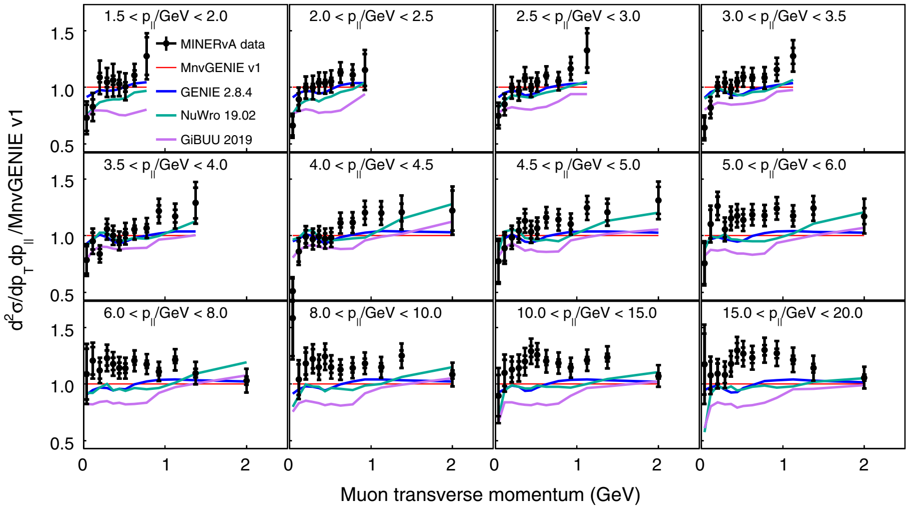
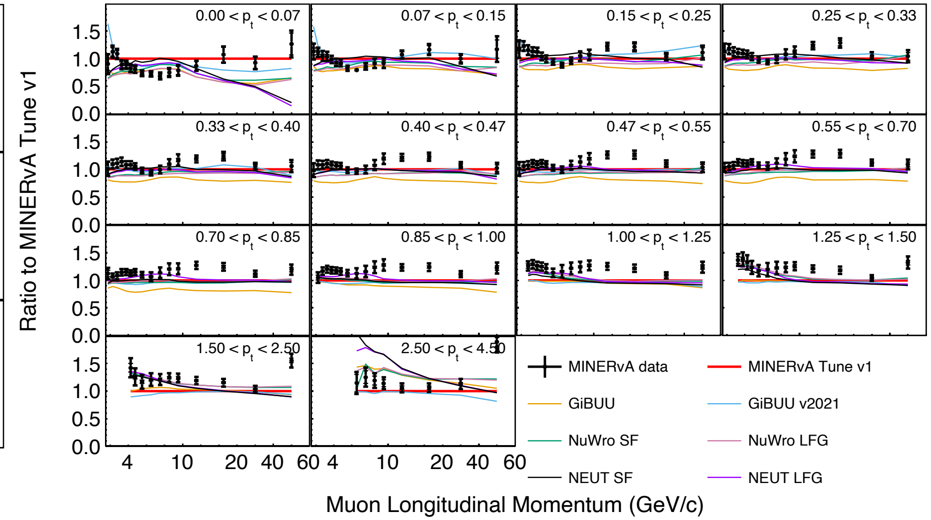
G18_10a	02_11a	Val	Val	BS	hA
G18_10a	02_11b	Val	Val	BS	hA
G21_11a	00_000	SuSAv2	SuSAv2	BS	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	BS	hA

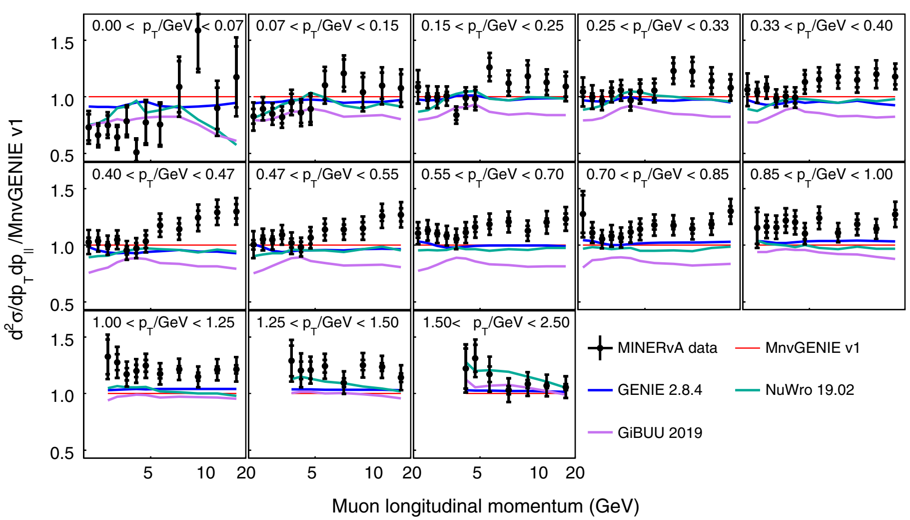
CC Inclusive Measurements

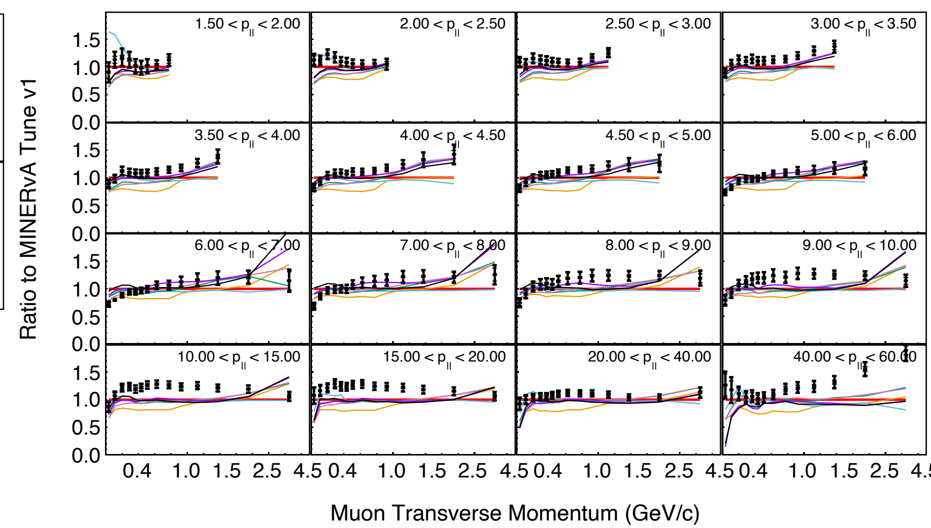
MINERvA <Eν> ~ 3.5 GeV



MINERvA <Eν> ~ 6 GeV

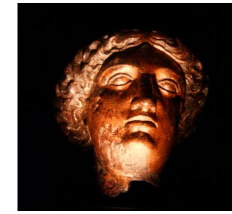




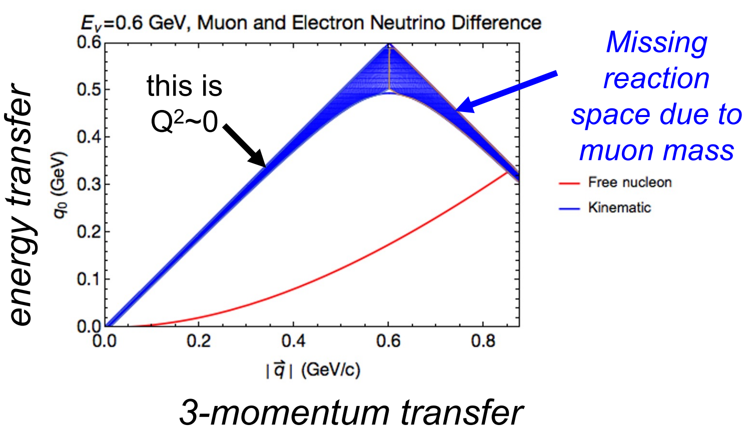


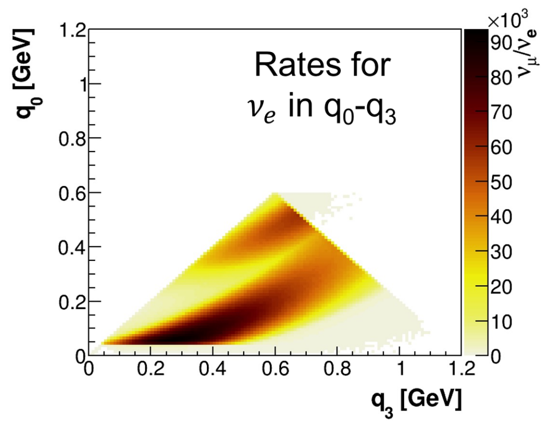
ν_e CC Inclusive Measurements

The ν_e Problem



- By necessity, our ν_μ rich beams have few ν_e in them to allow us to study any difference between ν_μ and ν_e interactions.
- Therefore, we infer ν_e interactions from studies of ν_μ
- But what we study can't give us the whole picture.
- Phase space (below), radiative corrections, nuclear effects.

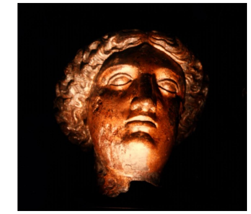


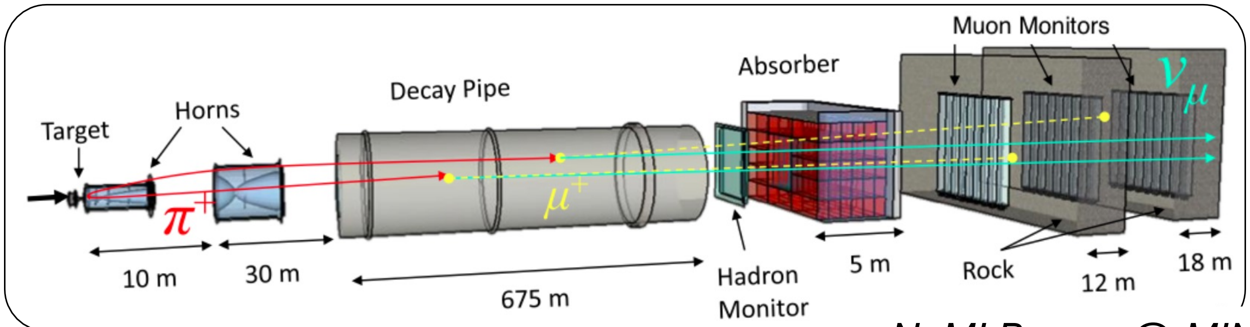


Radiative corrections:
O. Tomalak et al., Nature Commun. 13 (2022) 1, 5286 and Phys.Rev.D 106 (2022) 9, 093006

Nuclear effects:
T. Dieminger et al., Phys.Rev.D 108 (2023) L031301

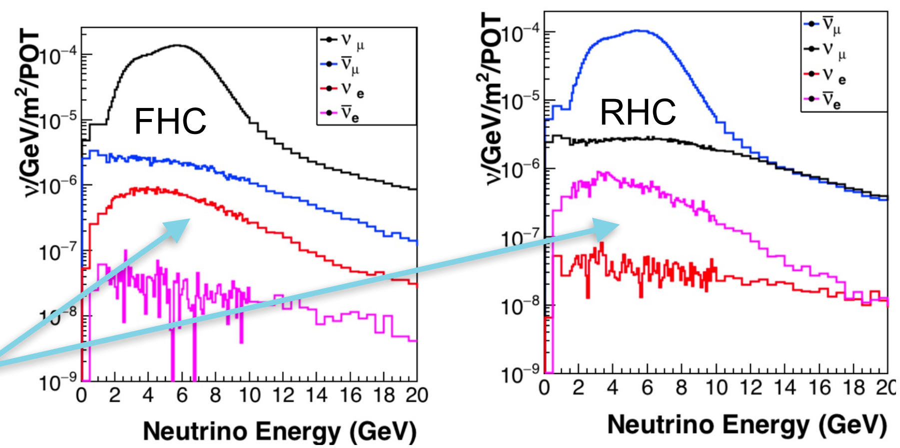
The NuMI Beam: Electrons





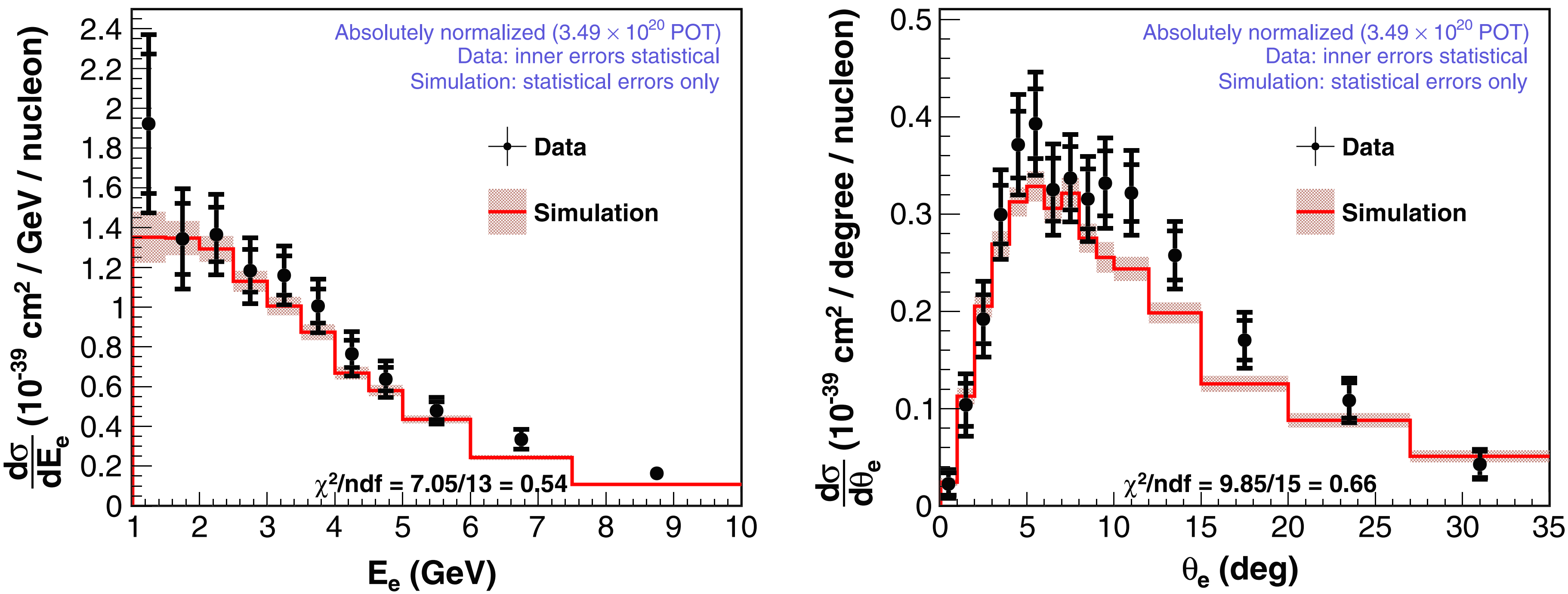
- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions.
- Pions decay mostly to muons, but weak decays involving electrons come from daughter muons, kaons, and so forth.
- ~1% contribution of the beam.

NuMI Beams @ MINERvA



ν_e CC Inclusive Measurements

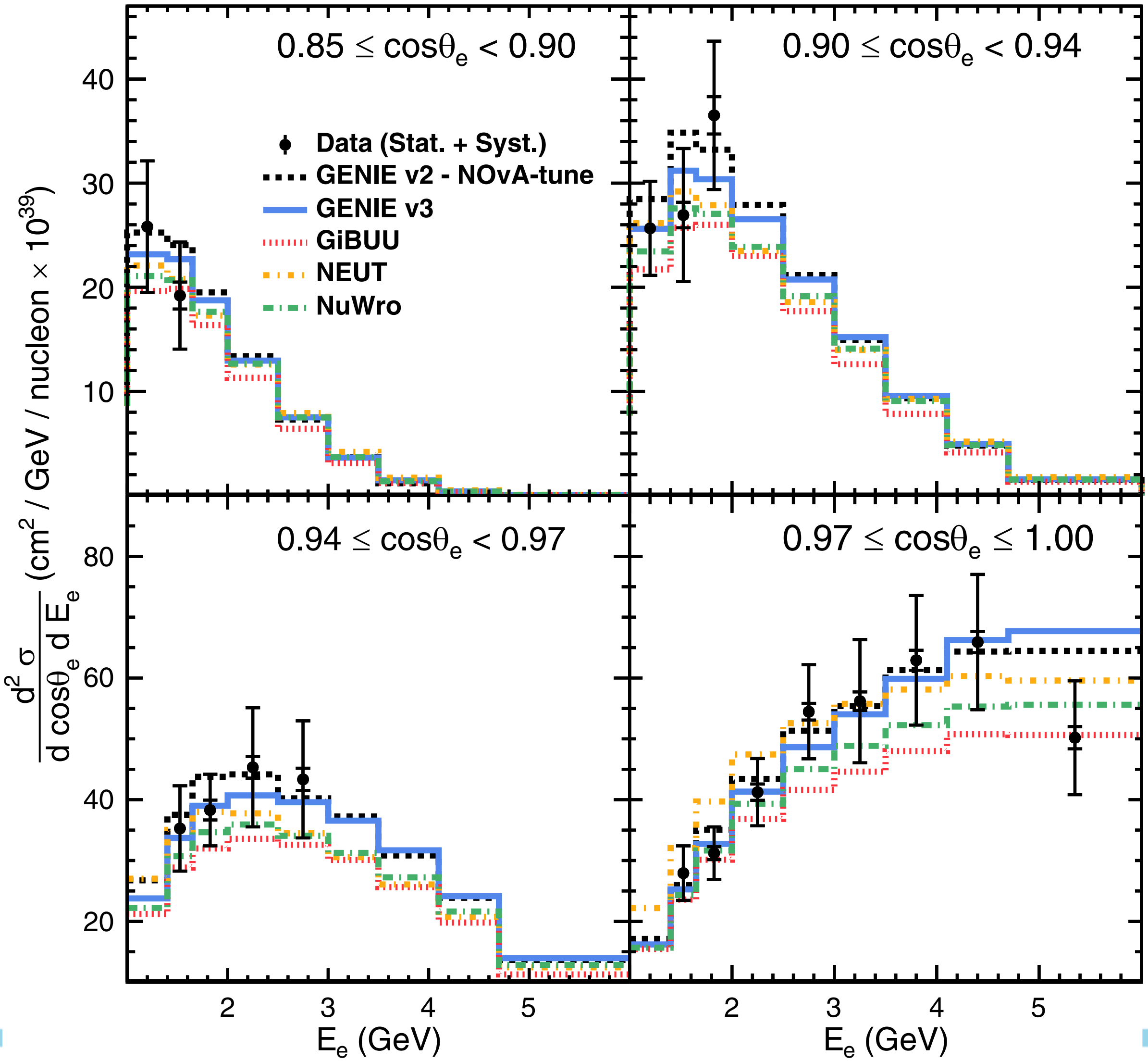
MINERvA, PRL 116, 081802 (2016)



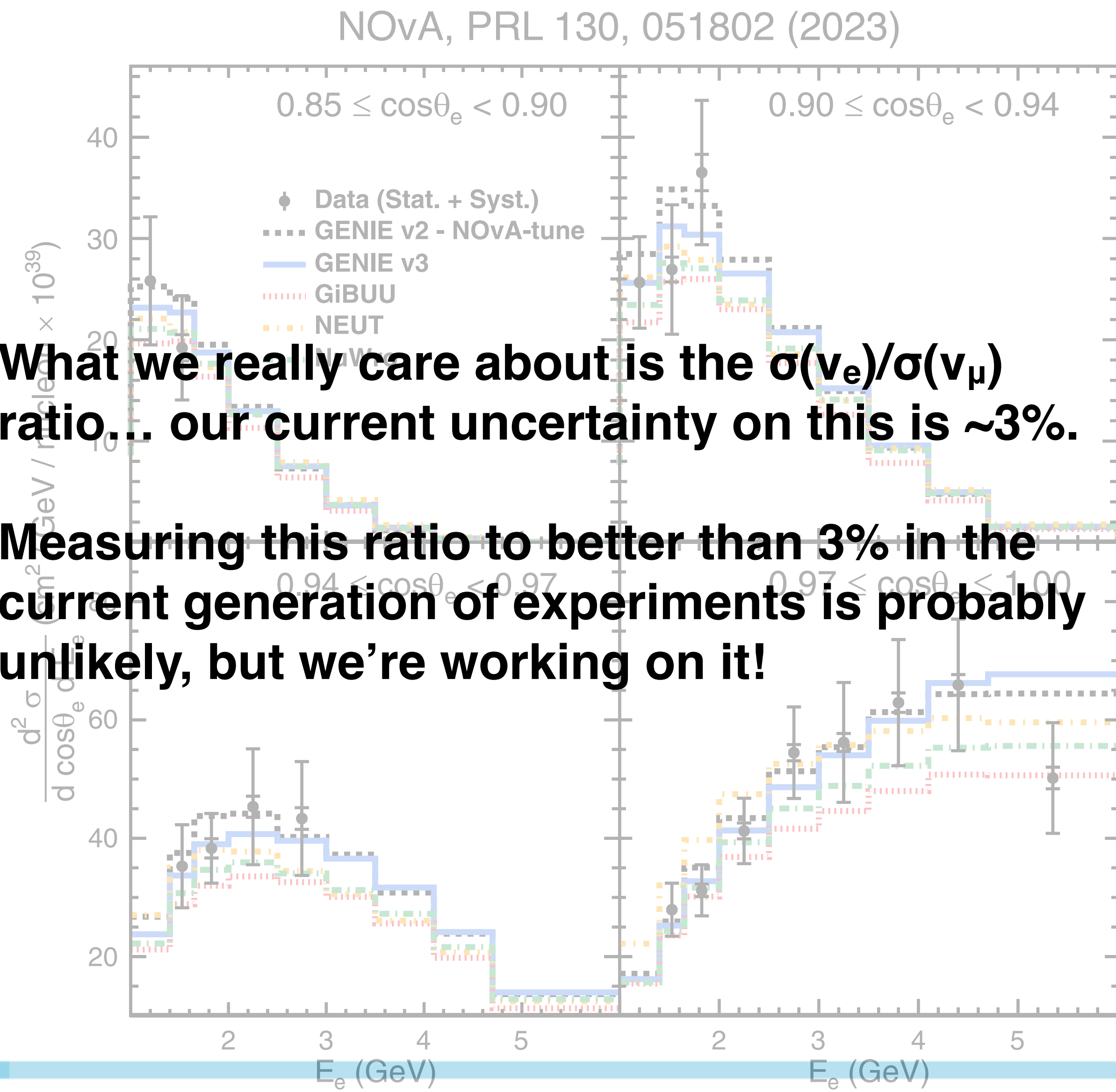
Fermilab

ν_e CC Inclusive Measurements

NOvA, PRL 130, 051802 (2023)



ν_e CC Inclusive Measurements



What we really care about is the $\sigma(\nu_e)/\sigma(\nu_\mu)$ ratio… our current uncertainty on this is ~3%.

Measuring this ratio to better than 3% in the current generation of experiments is probably unlikely, but we're working on it!

Summary of Measurements

- Overall most generators seems to okay predicting muon kinematics.
- When measuring pions directly, the predictions seem to be not too bad. But inclusive cross section measurements seem to imply that pion production is under-predicted at higher muon energies.
- There is something going on either with 2p2h or some other interaction that produces an enhancement of “available energy” at low momentum transfer for the higher energy experiments.
- How to make sense of all this?

Making sense of all these Measurements

- We are now faced with an enormous amount of data, some of which have few-percent uncertainties in the shape.
- Many generator developers are implementing some kind of global fit of their models to these data (and to electron scattering data too, but I don't have time to get into that).
  - Exclusive final-state measurements are easier to deal with.
  - GENIE uses the “Professor” tool (also used by Geant4)
  - NUISANCE is another great tool for comparing different data sets to different generator predictions.
- This is an enormously challenging task, and we are just getting started!

A Look to the Future

- There was much that I did not talk about:
  - Neutron measurements by MINERvA, ANNIE and others
  - Measurements of interactions in the SIS/DIS regime by MINERvA (and maybe NOvA someday)
  - Using electron scattering to constrain the vector components of our models (e4nu, electron scattering in neutrino generators)
  - Hadron scattering measurements to improve our understanding of FSI, secondary interactions in our detectors, and reducing flux uncertainties (ProtoDUNE, LArIAT, EMPHATIC, NA61, etc.)
  - BSM, NSI, LDM…
  - T2K ND280 Upgrade
  - DUNE 2x2, SBND
- Furthermore, all of the experiments will continue to analyze and improve upon existing measurements

A Look to the Future

- As we saw from the data, we have our work cut out for us to make sense of it all.
- But the future is bright, and we need smart people like you to help us…
- Come join the fun!