Lepton-Hadron Correlations in QE-like Neutrino Scattering at MINERvA

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NuINT 2022

Seoul

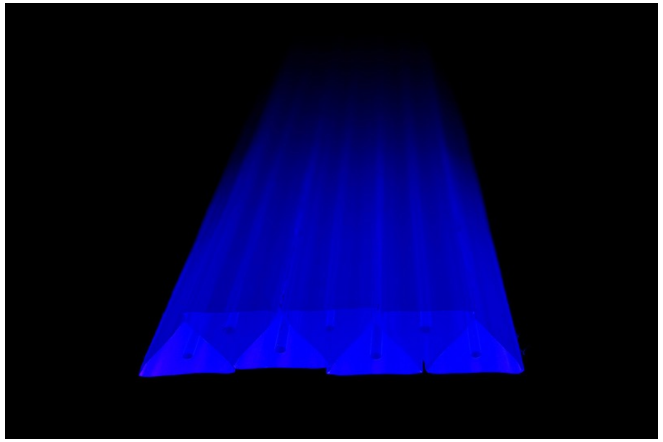
October 26, 2022

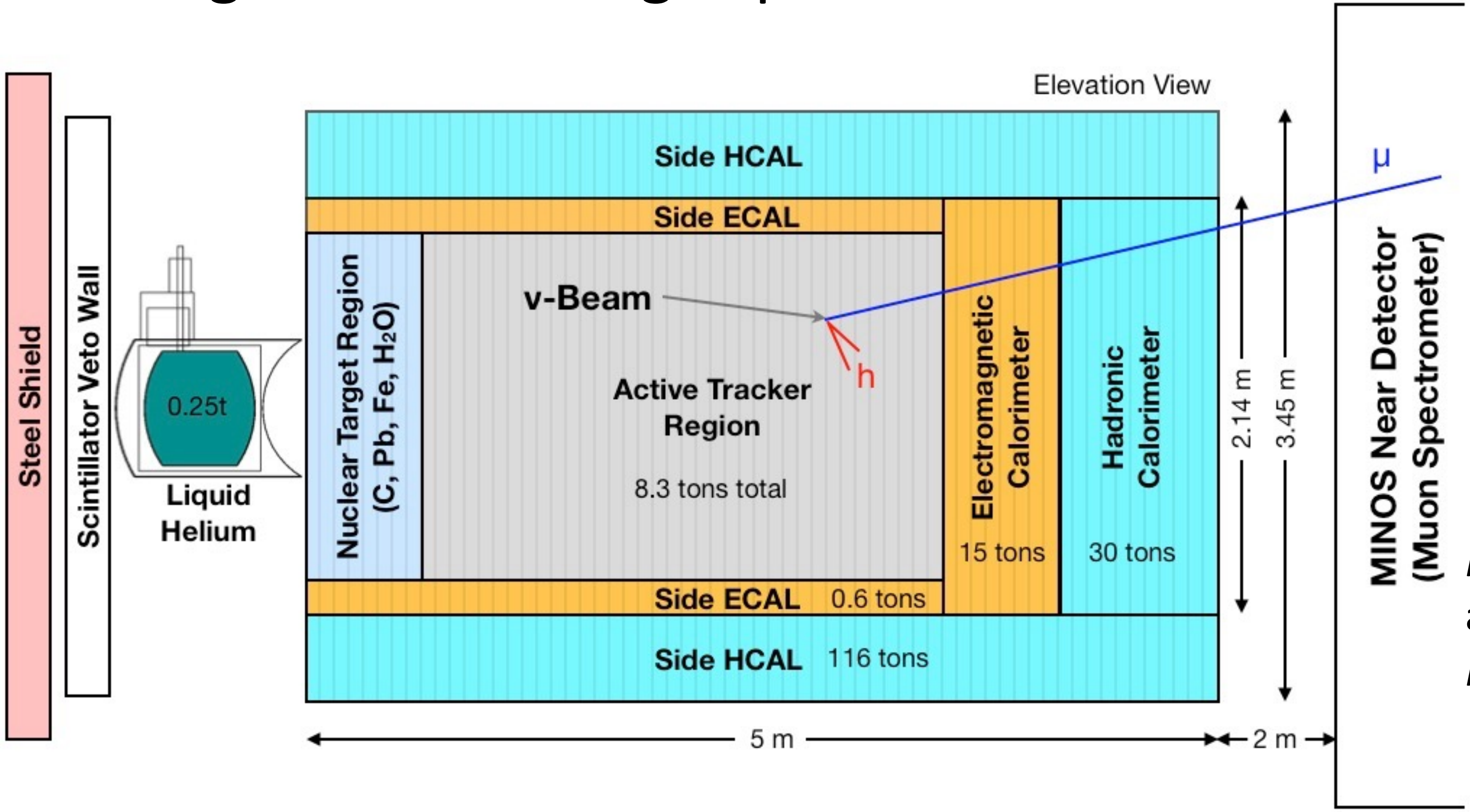
The Value of studying Lepton-Hadron Correlations in 0π events

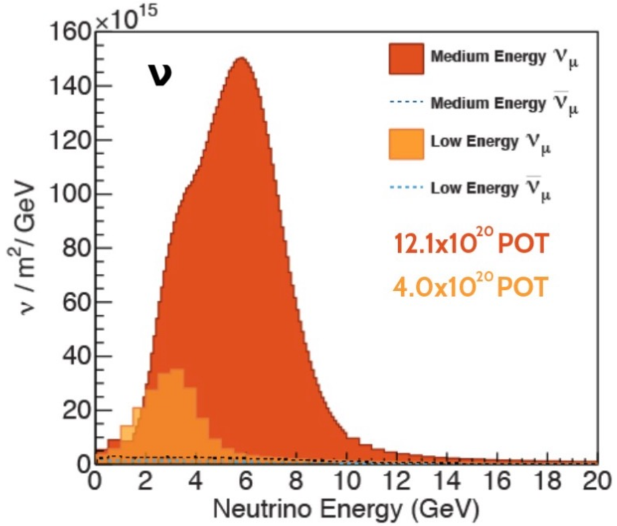
- Seeing many different processes that can contribute to 0pi events
- Recall from Monday: looking for neutron in exactly the right direction lets you measure scattering off Hydrogen
- Why study Lepton-Hadron correlations with 0pi events off CH using neutrinos?
  - Even on CH it's a well-defined system
  - If you only have protons leaving the nucleus in the final state, you can measure the proton kinetic energy well with Scintillator
  - 0π events are still the bulk of the event sample in oscillation experiments
  - Different "0π" processes on Carbon show up in different places in hadronic variables
- These results can be found in more detail in:
  - D. Ruterbories et al, *Phys.Rev.Lett.* 129 (2022) 2, 021803
  - M. Ascencio et al, *Phys.Rev.D* 106 (2022) 3, 032001

MINERvA's Neutrino Data Set

- High statistics
- Flux uncertainties <4%
- Fine-grained tracking & particle identification







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

What makes this analysis unique:

Cross sections are measured along 3 axes:

1) Muon longitudinal momentum: $p_{\|}$
   proxy for neutrino energy
2) Muon Transverse momentum: p_T
   proxy for momentum transfer (Q^2)
3) Total "available" Energy: ΣT_p

$E_{avail} \equiv$ (Proton and $\pi^{\pm}$ KE)

+ (E of other particles except neutrons)

for 0π events, this is simply sum of proton Kinetic Energy

- E_{avail} is what NOvA uses to translate from muon energy to neutrino energy

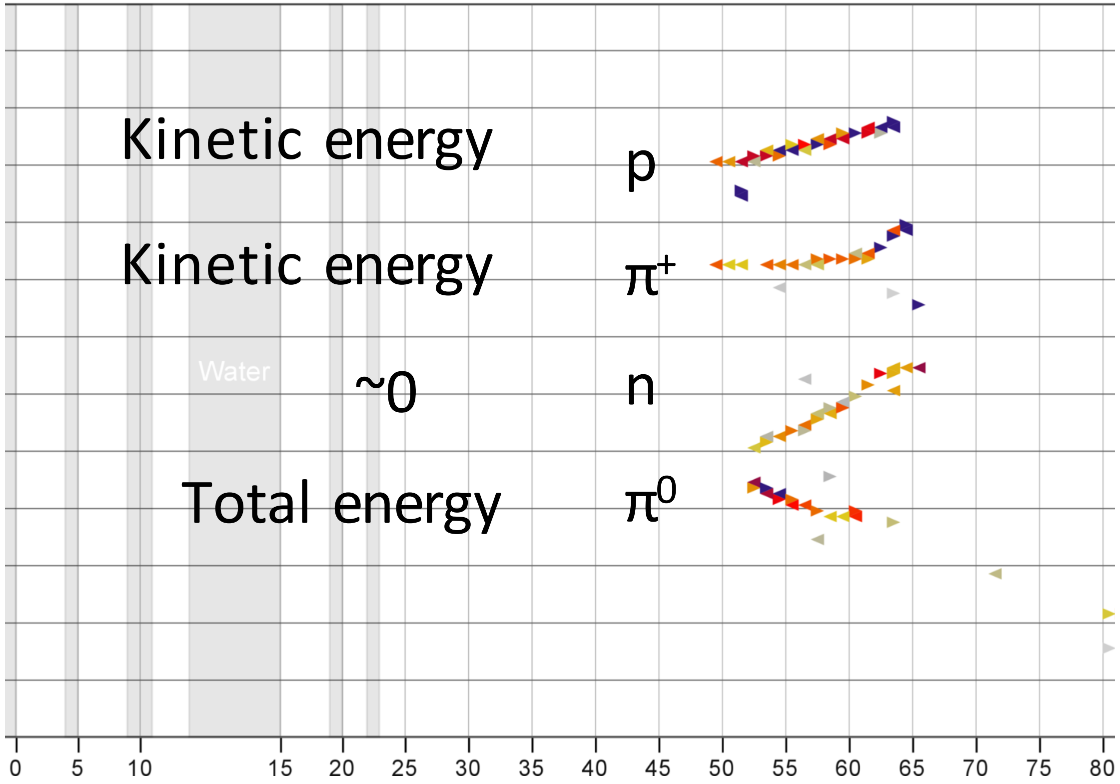
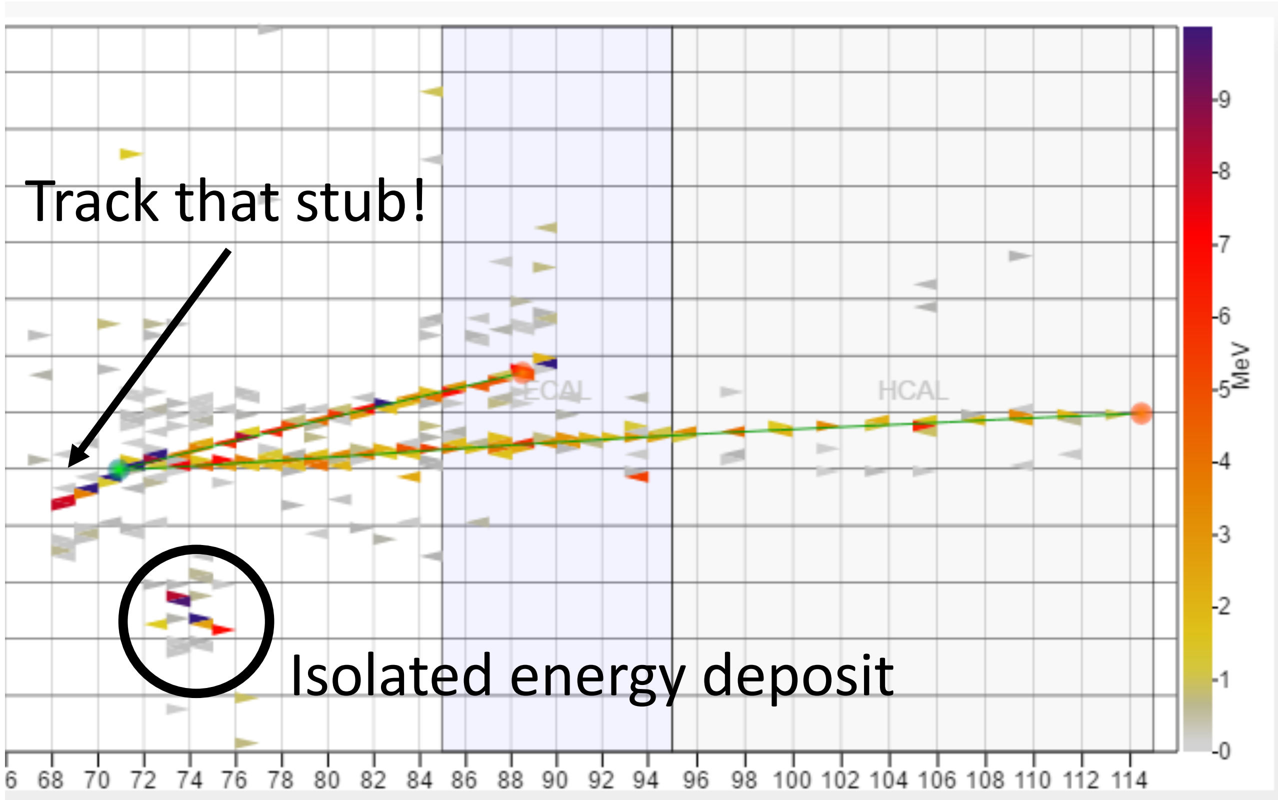


Figure courtesy P. Rodrigues

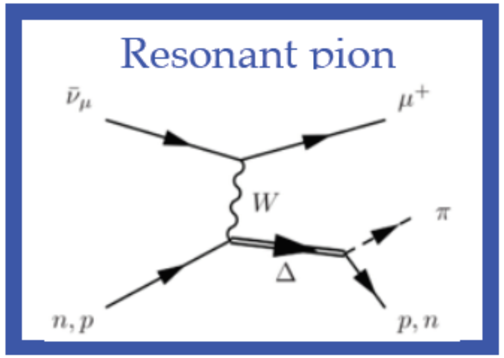
Event Selection for 0π Events @ MINERvA

- Track muons, pions and protons
- Measure dE/dx on all non-muon tracks
  - Must be consistent with proton
  - This vetoes events w/$\pi^{\pm}$
- Count all isolated energy deposits
  - must have <2 of them
  - This vetoes events w/ π^0
- Look for Michel Electrons (near all starts and ends of tracks)
  - must find 0
  - This vetoes events w/ π^+

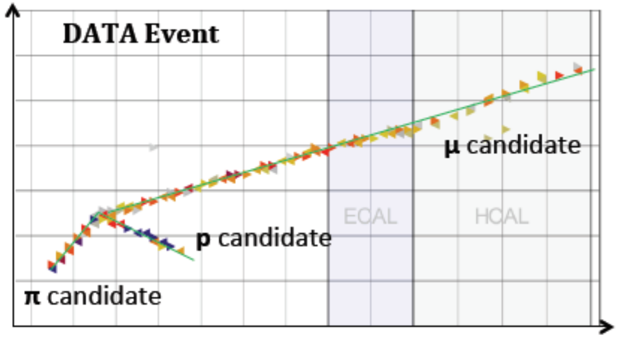


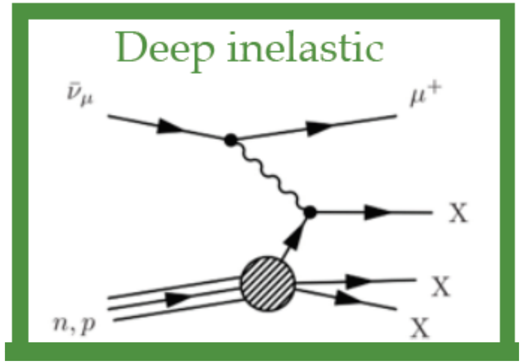
What are the backgrounds?

- Pion production (Resonant and non-resonant, neutral and charged pions):   Kevin's talk on Friday
- Inclusive (multi-pion) processes like SIS, DIS: Amy's talk on Monday

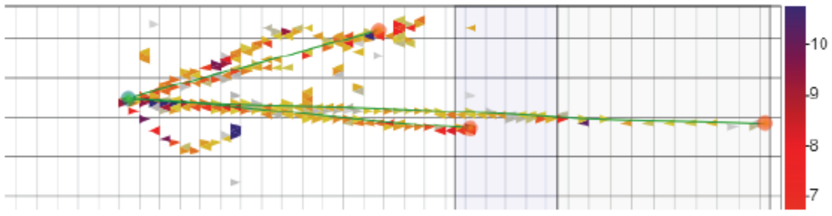


RES



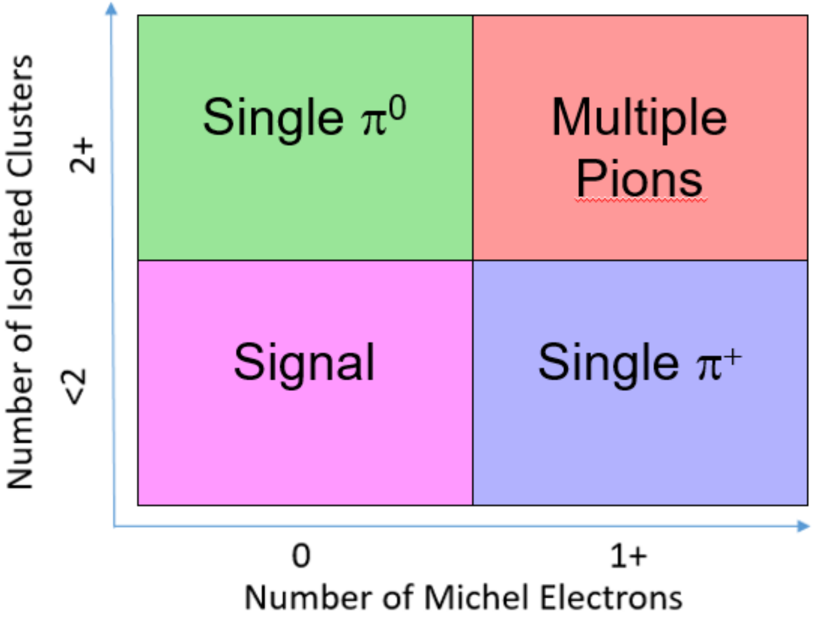


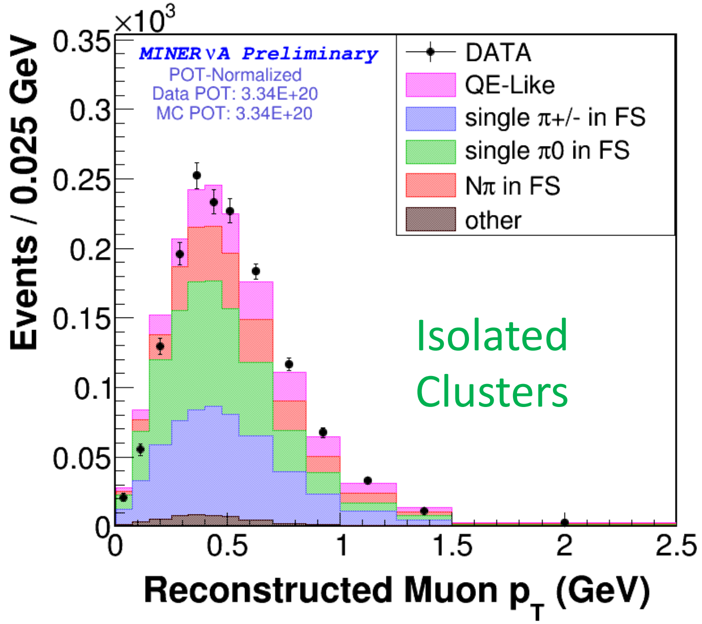
DIS

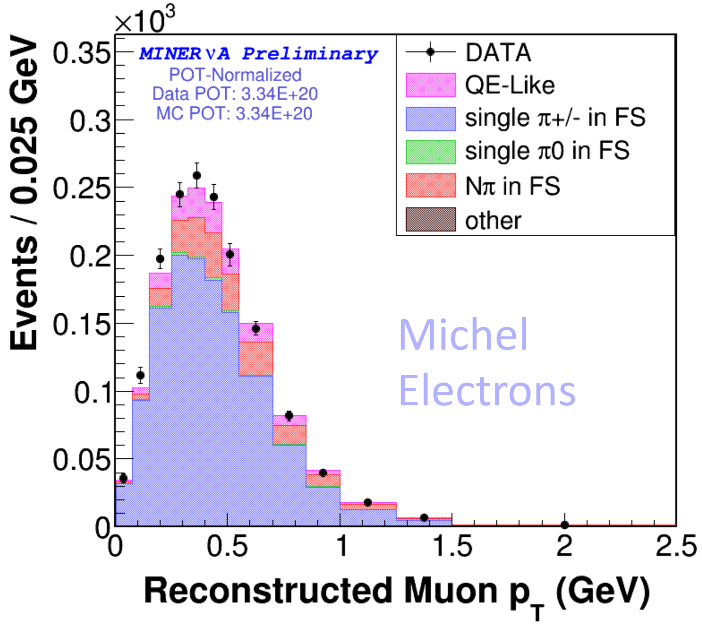


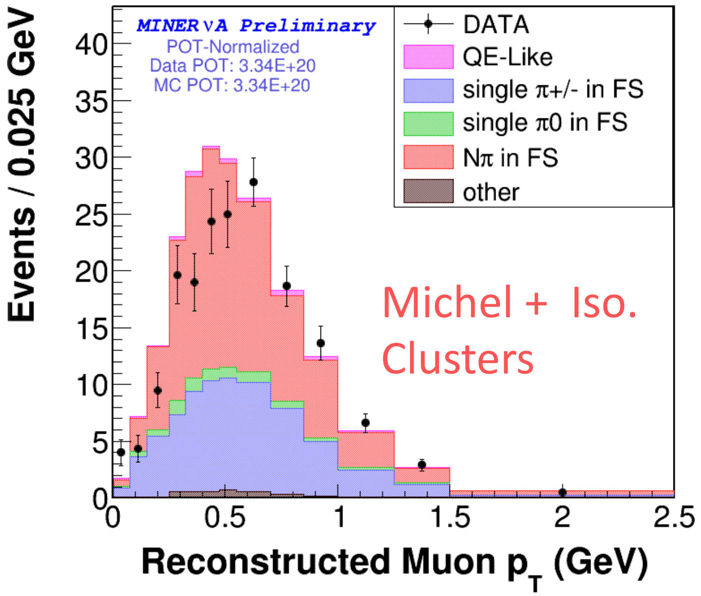
Three backgrounds= Three Sidebands

- Fit scaling factors as a function of p_t AND ΣT_p $\pi^{+/-}$,π^0,Nπ
- Sideband statistics: single pion sidebands have 0.2M each, multi-pion one has 57k events
- Use simulation to predict $p_{||}$ dependence









Ref: D. Ruterbories, FNAL Seminar 10/2019

Three backgrounds= Three Sidebands

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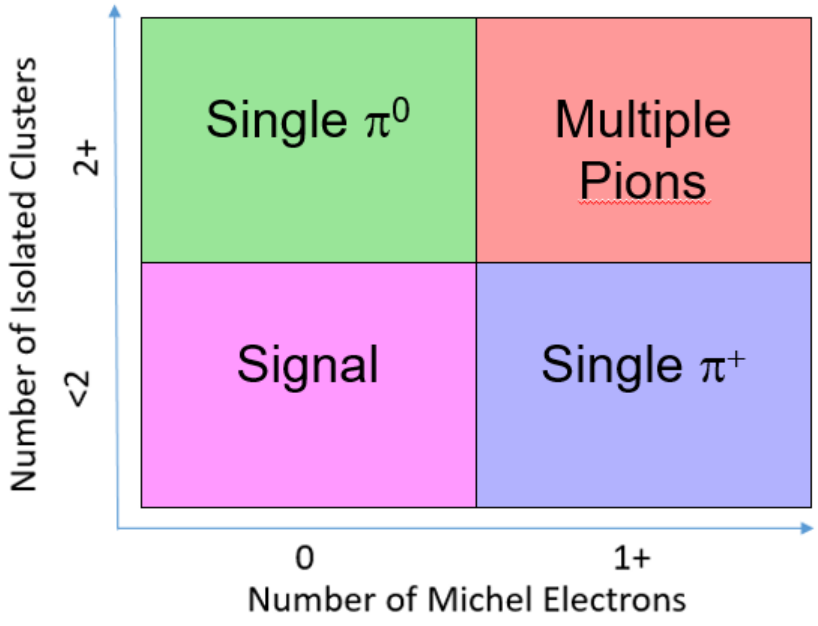
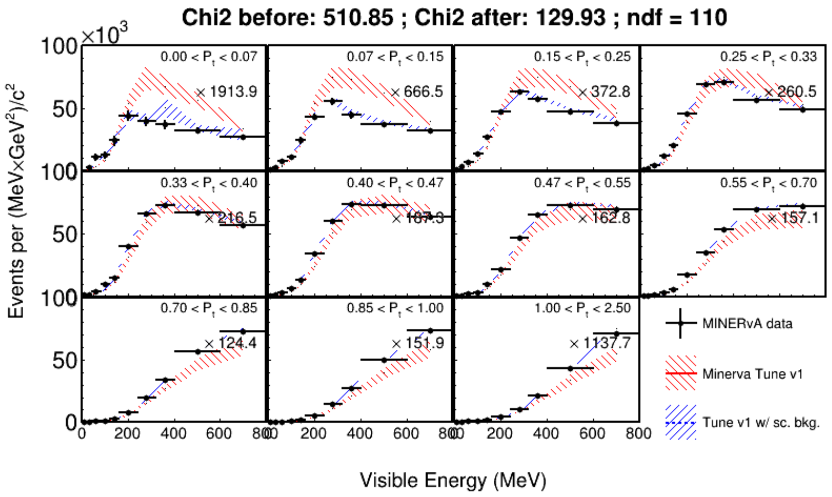
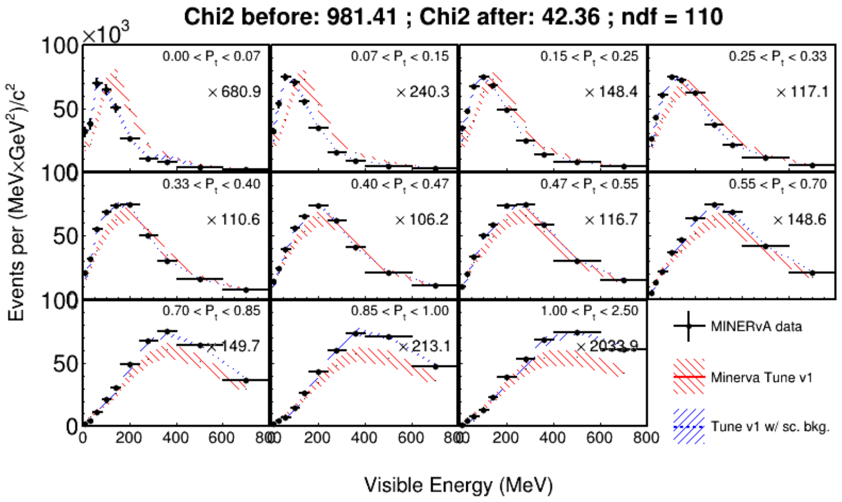


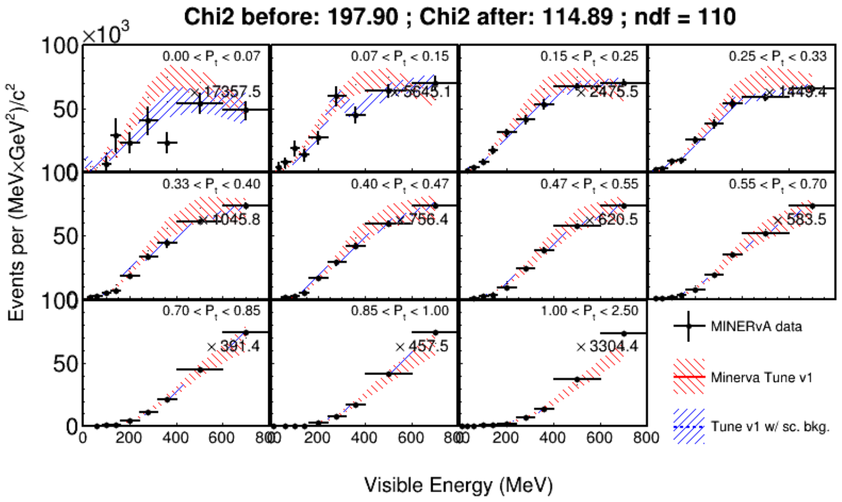
Isolated Clusters



Michel Electrons

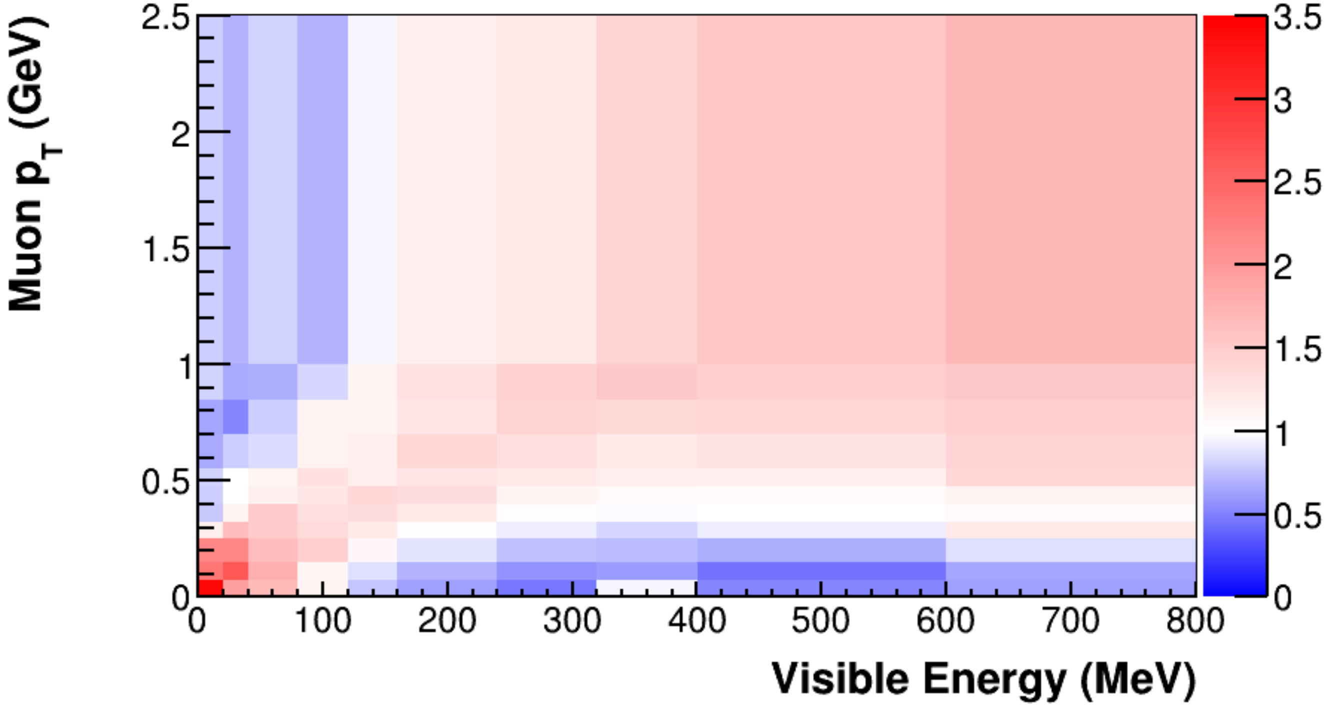


Michel + Isolated Clusters

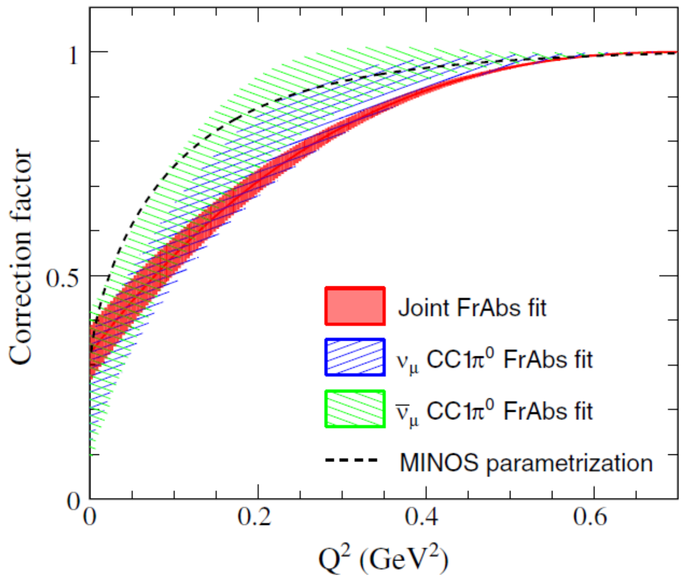


Ref: D. Ruterbories, FNAL Seminar 10/2019

Summary of Results from Background Fits:



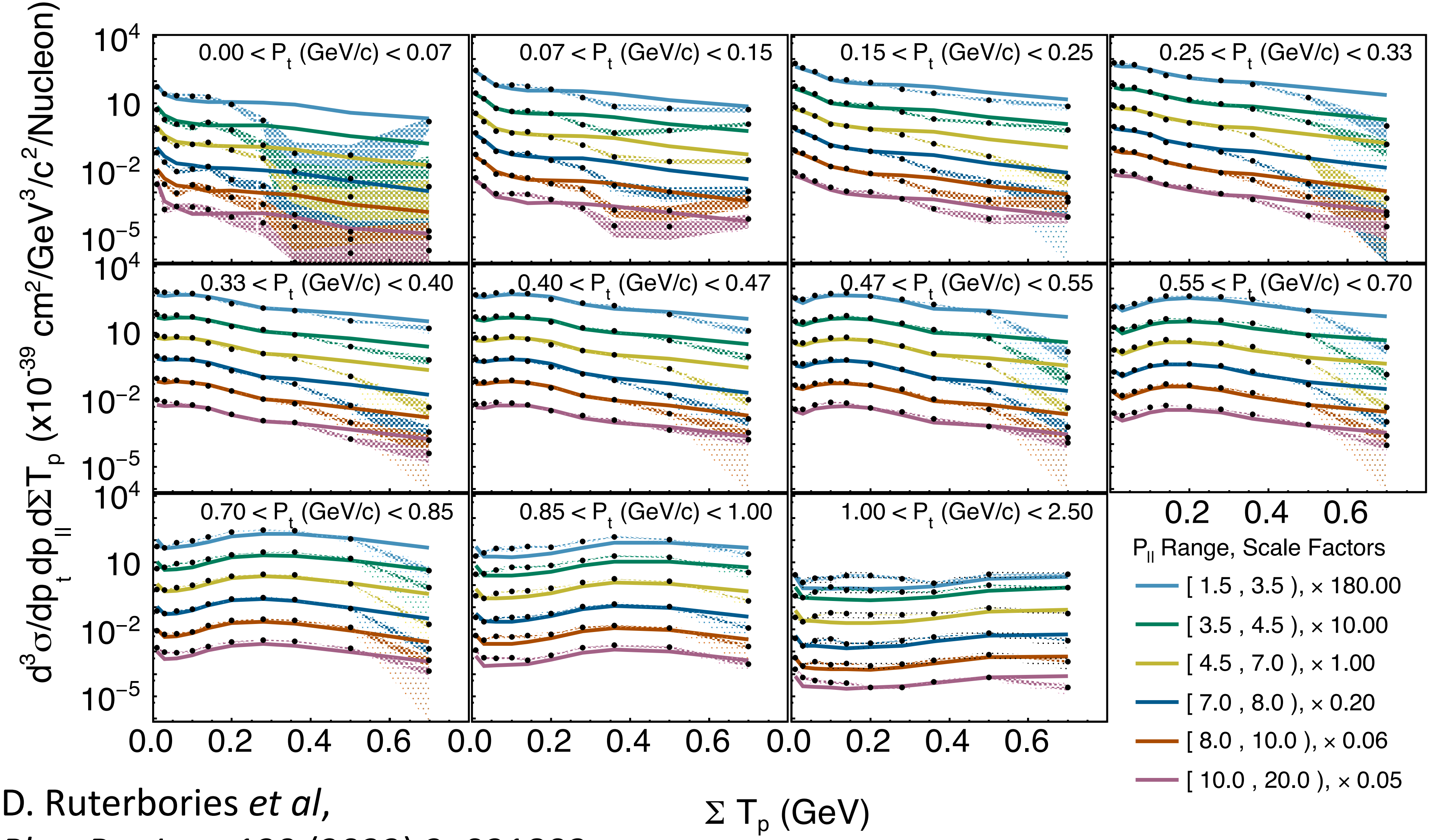
Phys. Rev. D 100, 072005 (2019)



Seen this before…. similar trend in "joint" fit from our Low Energy single π measurements

Ref: D. Ruterbories, FNAL Seminar 10/2019

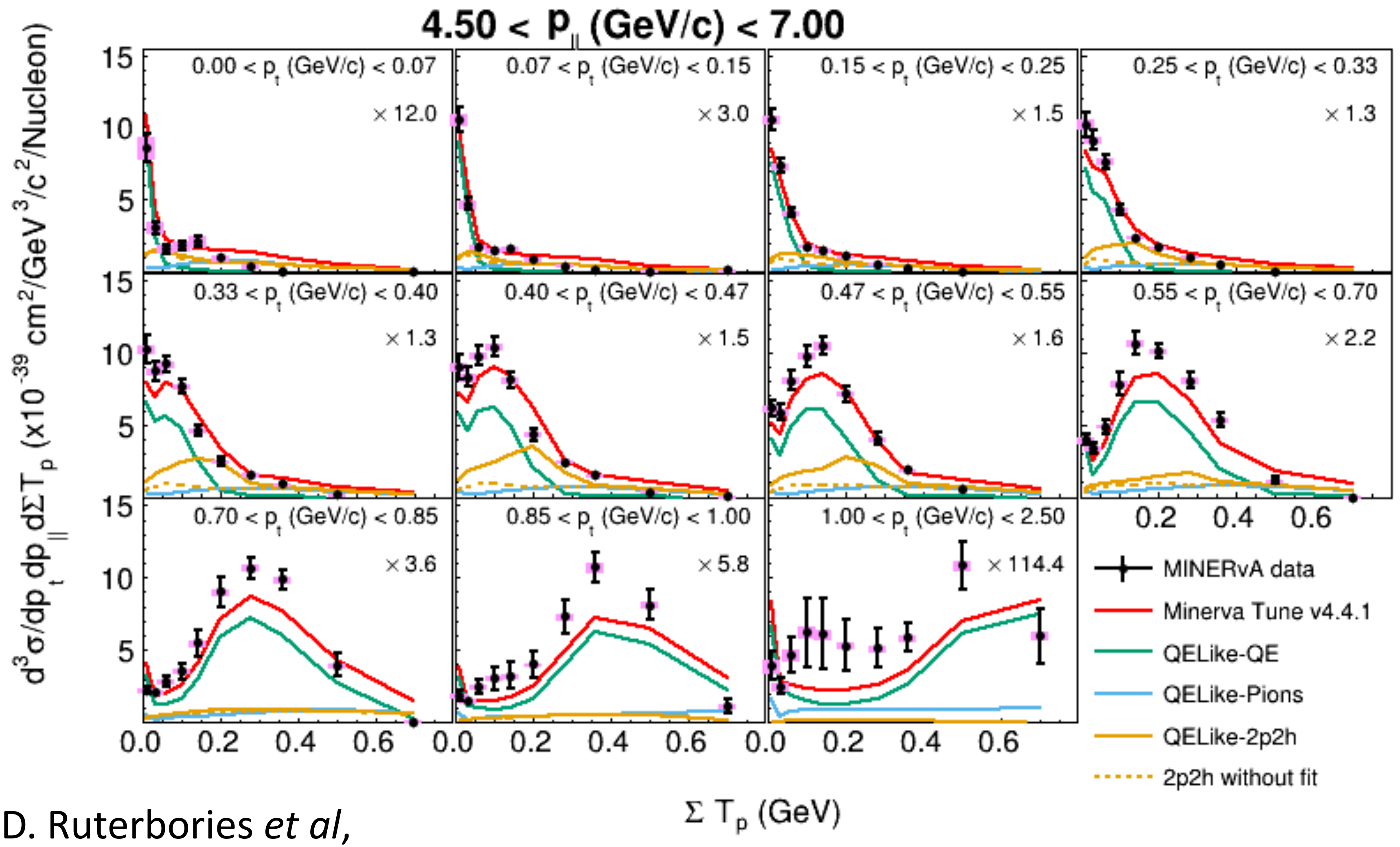
Subtract backgrounds, unfold in “3D”, and voilà



- The trends are independent of $p_{||}$
- 1.3M Events on predicted background of 0.4M
- Many processes contribute to ”CC0π ”
  - CCQE
  - 2p2h
  - Resonance+π absorption
  - DIS

D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022) 2, 021803

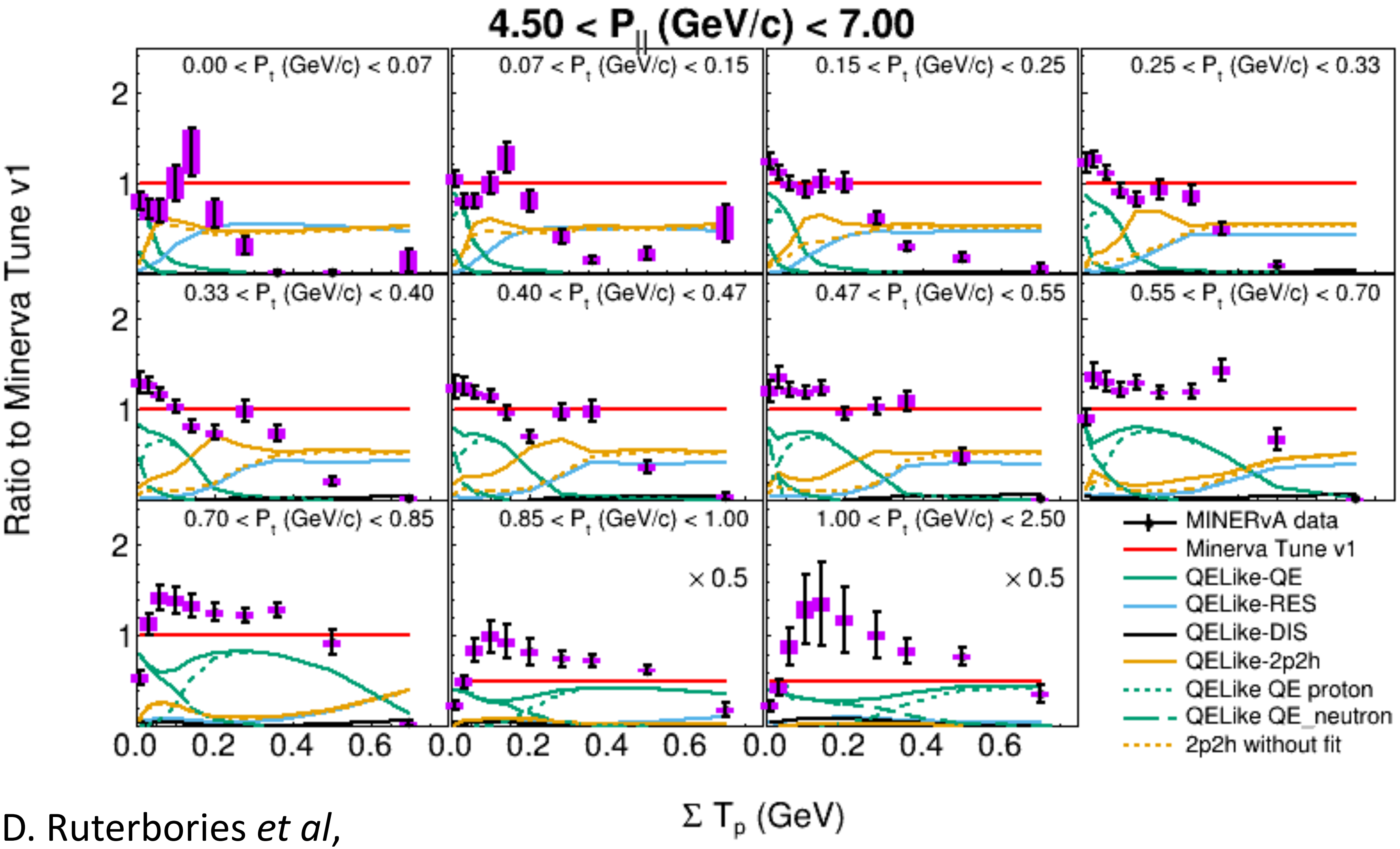
Consider one bin of $p_{||}$, now in 2D, ΣT_p vs p_T



- Many processes contribute to "CC0$\boldsymbol{\pi}$"
  - CCQE
  - 2p2h
  - Resonance+π absorption
  - DIS
- Lots of discrepancies with the model

D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022) 2, 021803

Consider one bin of $p_{\|}$, now in 2D, ΣT_p vs p_T



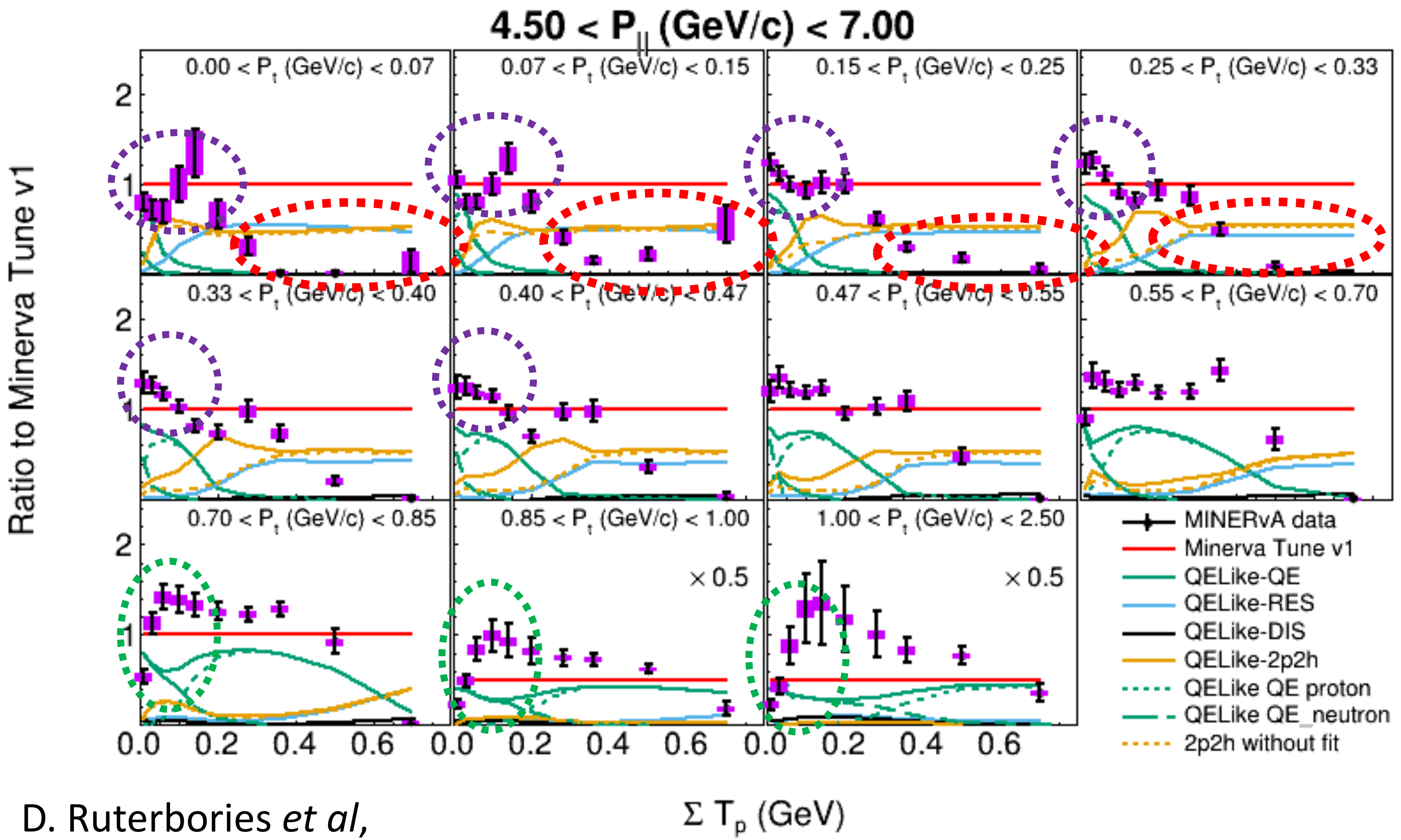
- Many processes contribute to "CC0$\boldsymbol{\pi}$"
  - CCQE
  - 2p2h
  - Resonance+π absorption
  - DIS
- Where does the model come from?

D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022) 2, 021803

The “MINERvA Tune”

- In our 3GeV data, we found discrepancies compared to generators (GENIE) out of the box that surpass the standard “GENIE” uncertainties.
- MINERvA has developed a model tune in use today that better describes its own CH data than do untuned generators, based on
  - Theory and models implemented in GENIE 2.12.x → 3.0.x,
  - D_2 bubble chamber data (in particular for non-resonant pion production),
  - and MINERvA’s own measurements from Low Energy data (extra 2p2h)

Consider one bin of $p_{\|}$, now in 2D, ΣT_p vs p_T



Discrepancies:

- QE peak discrepancy at low ΣT_p: small change in ratio but biggest cross section change
- Low p_T high ΣT_p events predicted as 2p2h and stopped pions are almost absent in the data.
- Highest p_T low ΣT_p events, events where the leading proton's energy ends up as neutrons through final state interactions, are also overpredicted.

D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022) 2, 021803

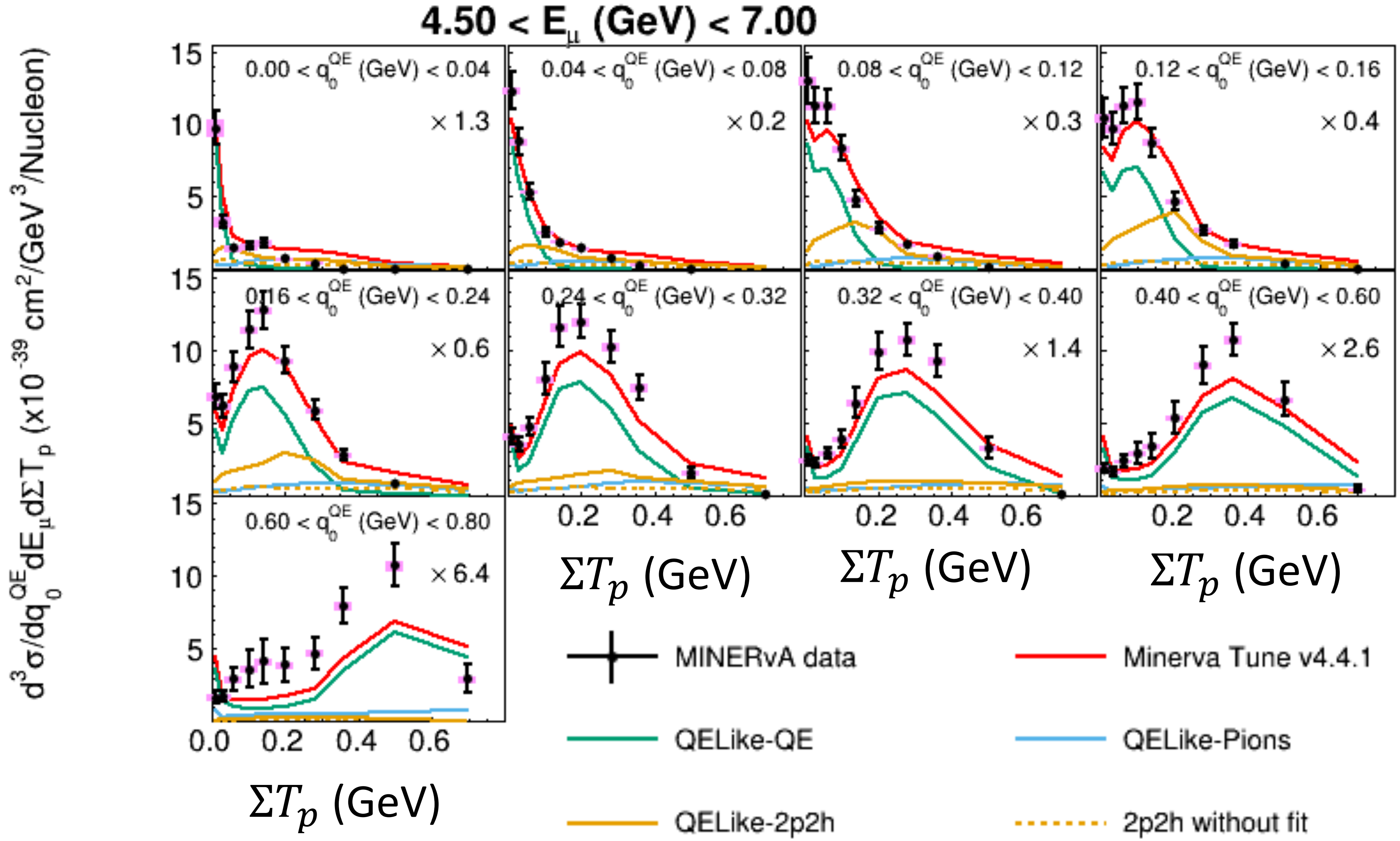
What does this mean for Oscillation Experiments?

- Goal: Measure Oscillations versus NEUTRINO ENERGY, not $\Sigma T_p, p_T, p_{\parallel}$
- Consider T2K and NOvA (or HK and DUNE):
  - T2K/HK determine neutrino energy by adding muon energy and " q_0^{QE} ", meaning the energy transferred to the nucleus, under QE hypothesis:

$$E_{\nu,QE} = \frac{M_n^2 - (M_p - E_b)^2 - M_\mu^2 + 2(M_p - E_b)E_\mu}{2(M_p - E_b - E_\mu + P_\mu \cos(\theta_\mu))}$$

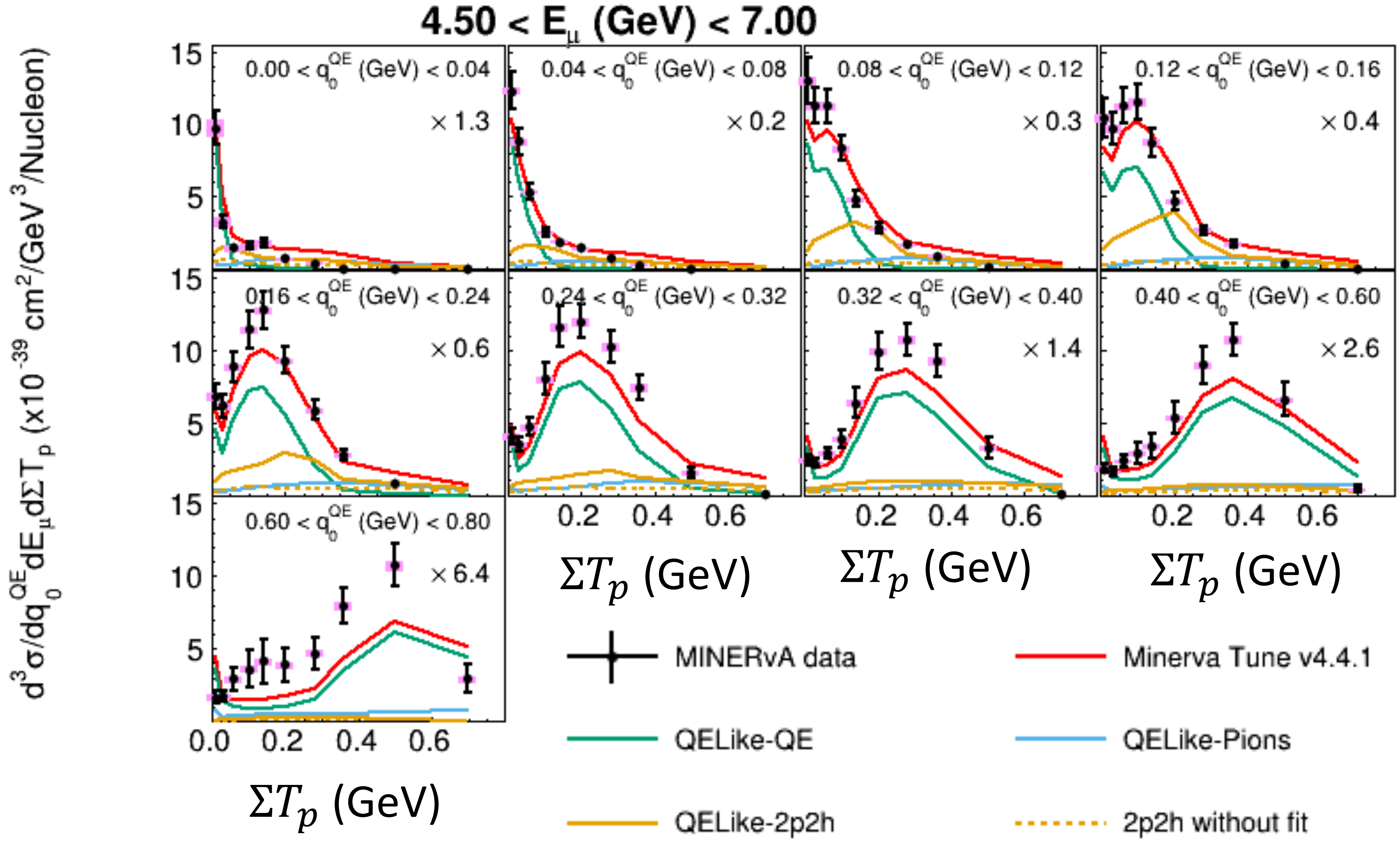
  - NOvA and DUNE determine neutrino energy by taking muon energy and adding measured hadronic (ΣT_p, here) energy to it, with a model to translate hadronic energy to "true hadronic energy"
- Do these two prescriptions give you the same neutrino energy?
  - At least on average?

Comparing 2 proxies for Neutrino Energy:



- T2K and HK: q_0^{QE} gets added
- NOvA, and LAr: add visible recoil energy
- The two don't agree with the model for 0π events
- Events where the QE hypothesis says there should be lots of proton energy added, MINERvA does not see that energy!

Comparing 2 proxies for Neutrino Energy:

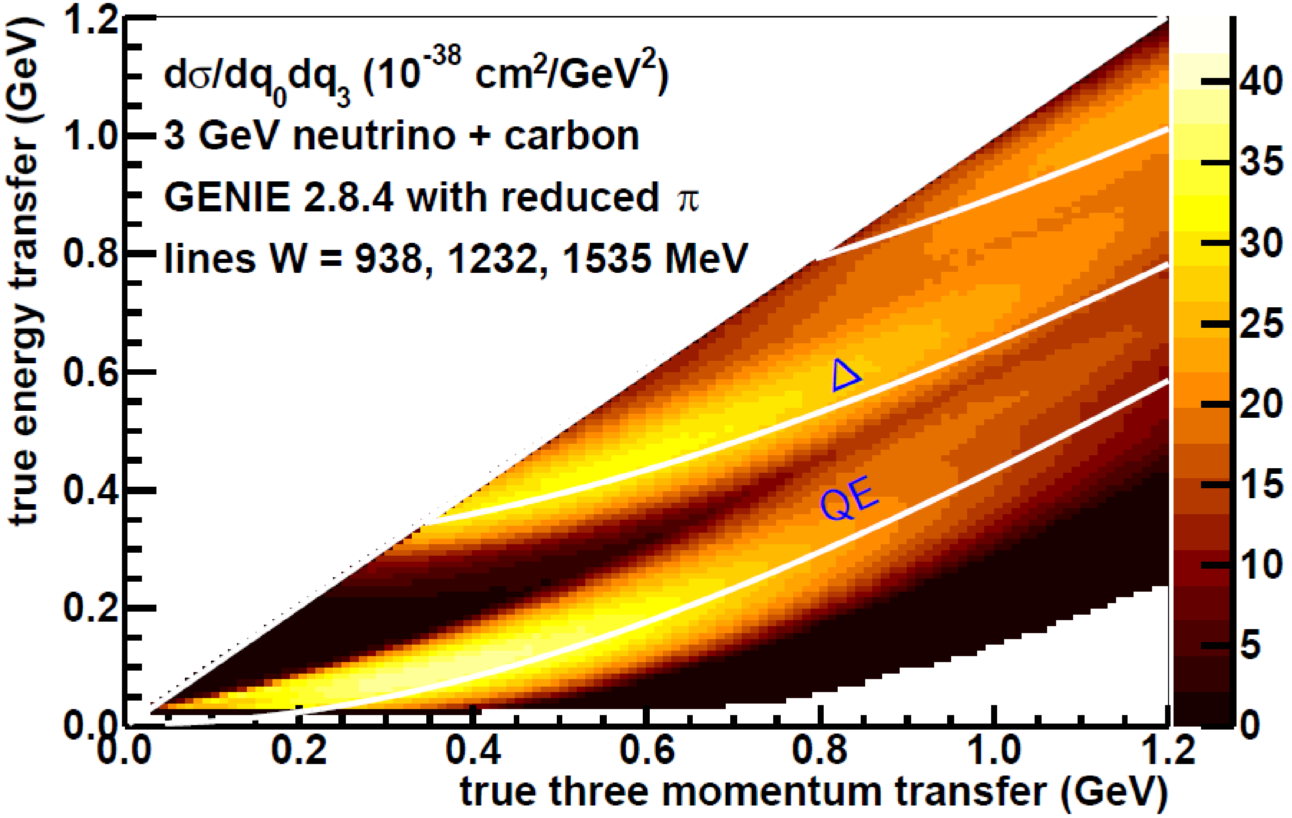


- Do models do any better on combination of QE and resonant events in describing available energy?

D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022) 2, 021803

A more inclusive look at low q_0 events…

- Recall how QE and resonant events appear in q_0-q_3 space:



Phys. Rev. Lett. 116, 071802 (2016)

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$
$$E_\nu = E_\mu + q_0$$
$$q_3 = \sqrt{Q^2 + q_0^2}$$

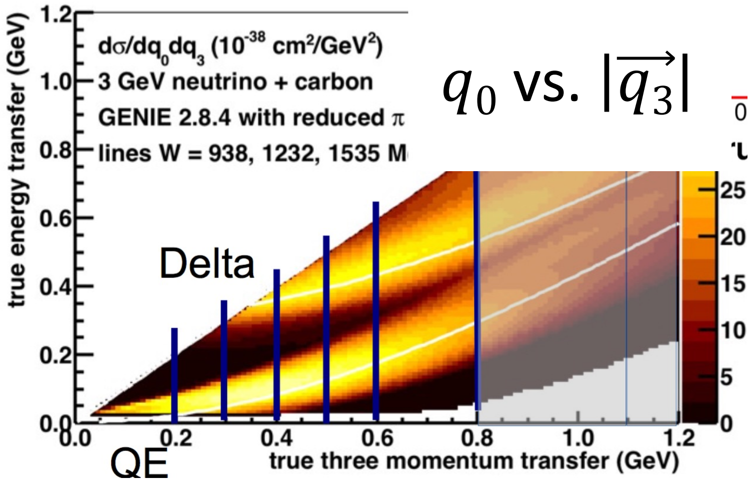
Event selection:

1) Require μ of the correct charge
2) Sum up all the recoil energy=Available Energy
3) Calculate q_3 using above formulae
4) Extract cross sections vs AVAILABLE energy

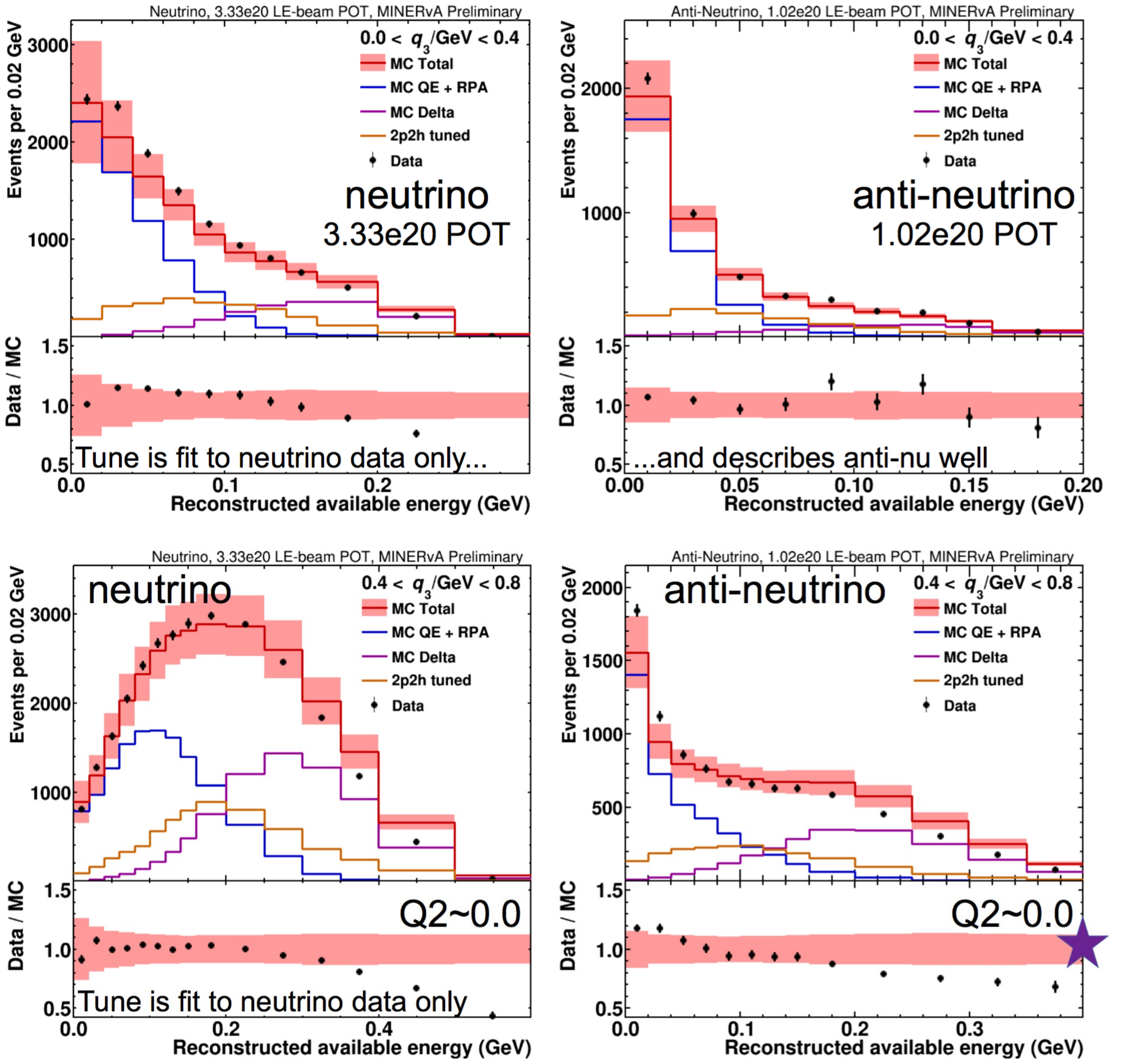
Reminder: MINERvA ν_μ & $\bar{\nu}_\mu$ "low q_0" from LE Beam:

- Low recoil "Inclusive CC" ν_μ interactions

Phys. Rev. Lett. 116, 071802 (2016) and
Phys. Rev. Lett. 120, 221805 (2018)



- Tune model (extra 1p1h or 2p2h) to fill in dip region between QE & Δ.
- This tune from neutrino data also agrees with antineutrino data!
- Remaining problem is low Q² region, consistent with pion production.

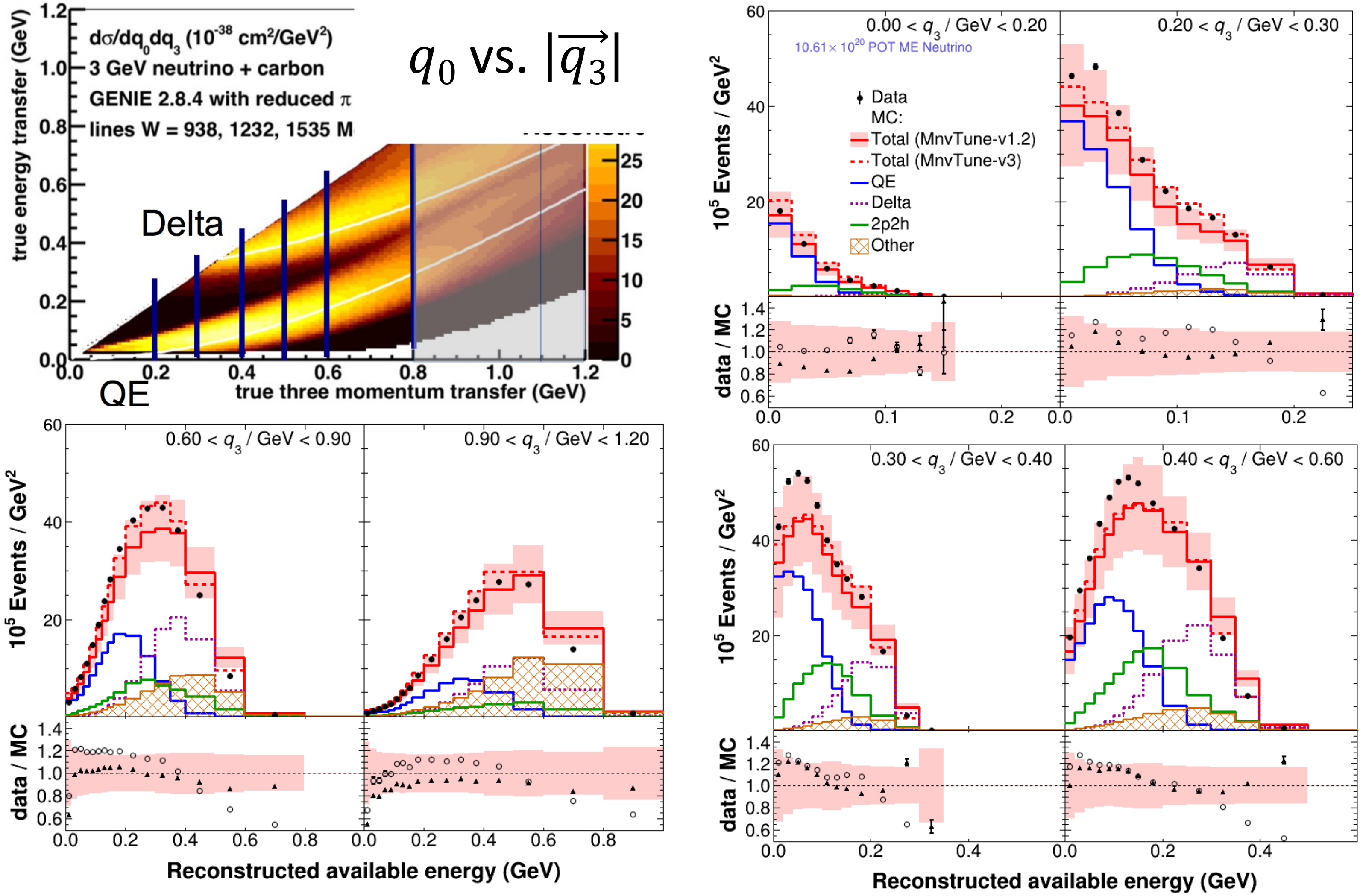


New "low q_0" Results from Medium Energy Data

- New data sample still sees need for 2p2h
- QE peak not quite right here either…
- Also see overprediction for pion production
- Other news: several new models of 2p2h process are now available for comparison (NuWRO, SUSAv2)

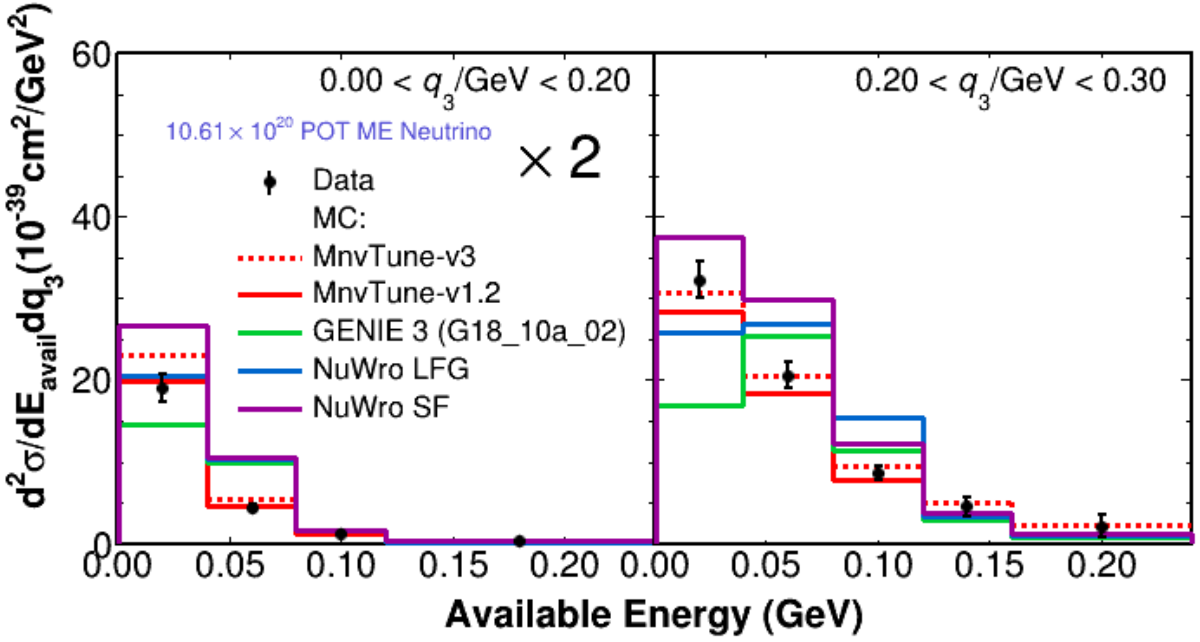
M. Ascencio et al, *Phys.Rev.D* 106 (2022) 3, 032001

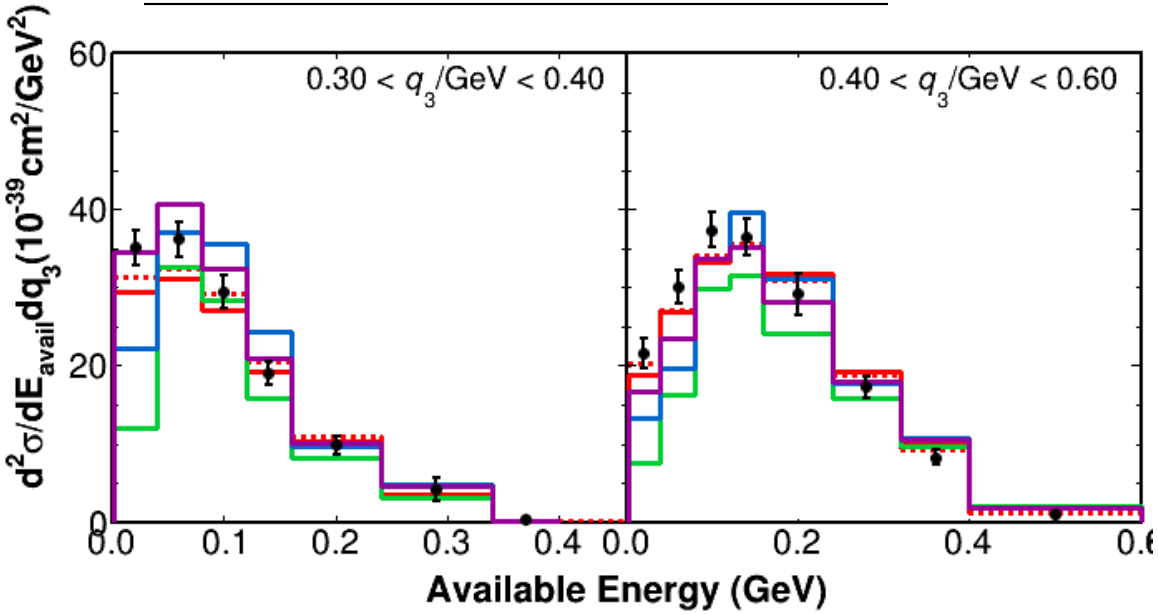
q_0 vs. $|\overrightarrow{q_3}|$

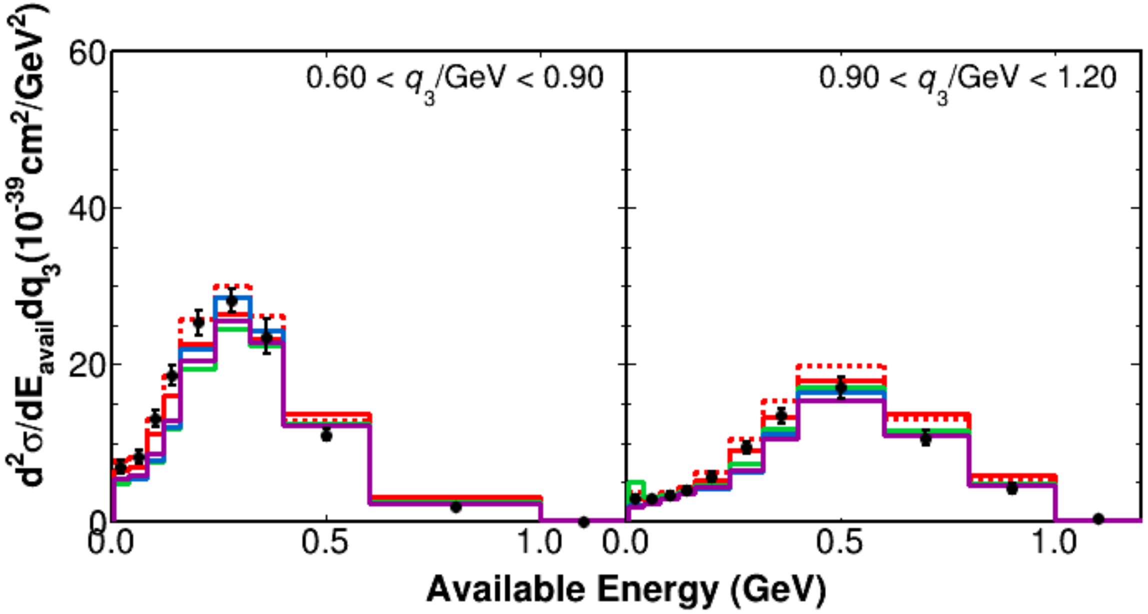


New q_0 Model Predictions

MC/Generators	χ^2	χ^2/NDF
MnvTune-V3	1100.8	25.
MnvTune-V1.2	963.2	21.9
NuWro SF	9981.8	226.9
NuWro LFG	16363.8	371.9
GENIE 3 (G18_10a_02)	14148.9	321.6







Conclusions

- MINERvA looking at lepton-hadron correlations in many new samples at low recoil:
  - These are the events that the oscillation community will be using!
- **Using current model to compare two different techniques of neutrino energy reconstruction does NOT agree with data!**
- Lots of new models on the market to compare to these data thanks to the puzzles we found in the low energy data set
- Current models overpredict 2p2h and/or stuck pions in 0π events, and overpredict lowest recoil un-stuck pions in scintillator
- What's next? Measuring 2-d cross sections vs low recoil for ν_e and $\bar{\nu}_e$ samples
- Next talks: what do we see in antineutrino data? What about other nuclei?


감사합니다

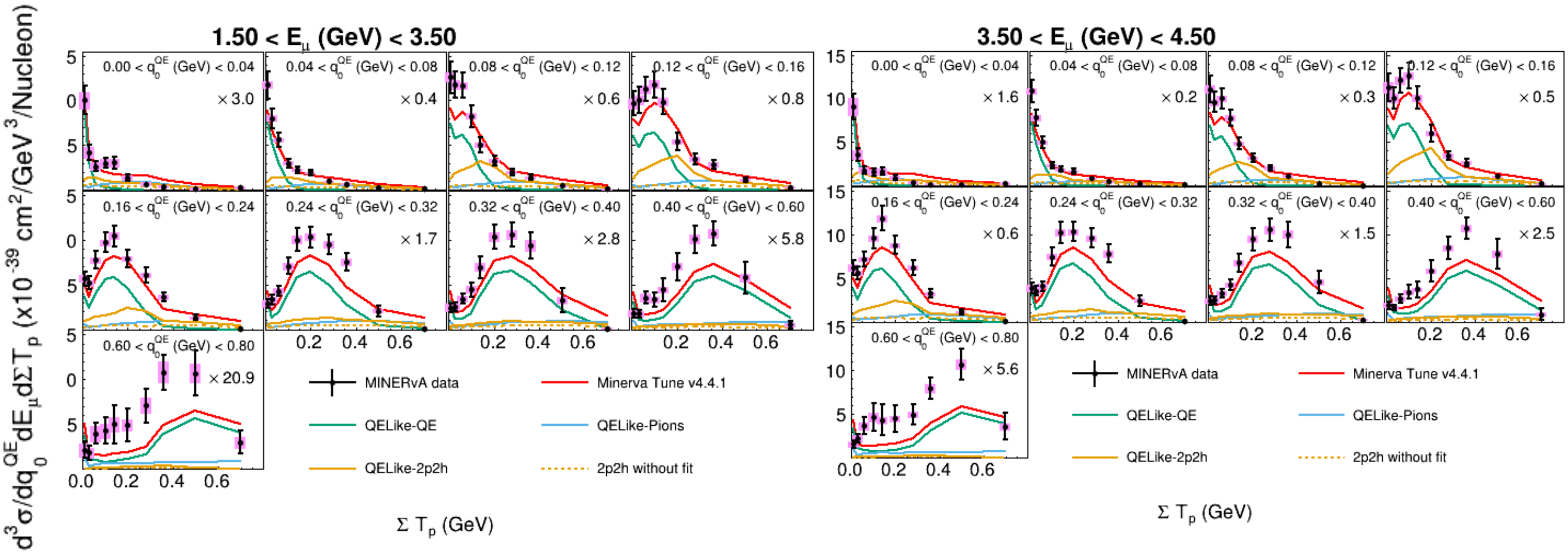
Backups

MINERvA Tunes: v1 for experts

- GENIE 2.12.6
- Physics Model Modifications
  - Non-resonant pion production * 0.43
  - RPA suppression of CCQE
  - Nieves 2p2h
  - Low recoil analysis constraint
  - MaRes -> 0.94 from 1.12
  - CCNormRes -> 1.15 from 1.0
- MnvTune.v1.2: MnvTune.v1 plus the suppression pion coherent production seen in LE beam
- MnvTune.v2: add low Q^2 suppression in pion production
- MnvTune.v3: +enhanced Bodek-Richie tail for QE, SUSA 2p2h model, plus Removal Energy for pion production

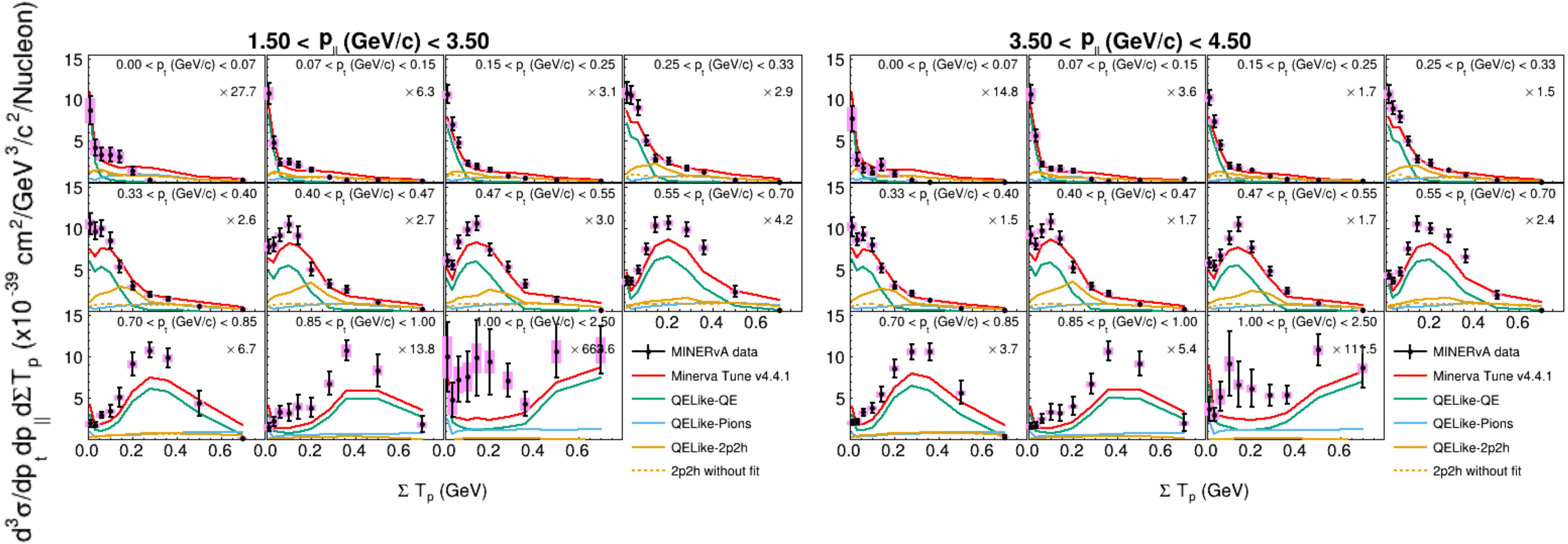
These take into account the full bubble chamber fit

Neutrino Energy proxies at lower $p_{\parallel}$



D. Ruterbories *et al*,
Phys.Rev.Lett. 129 (2022) 2, 021803

Charged Current 0π Cross Sections at lower $p_{\parallel}$



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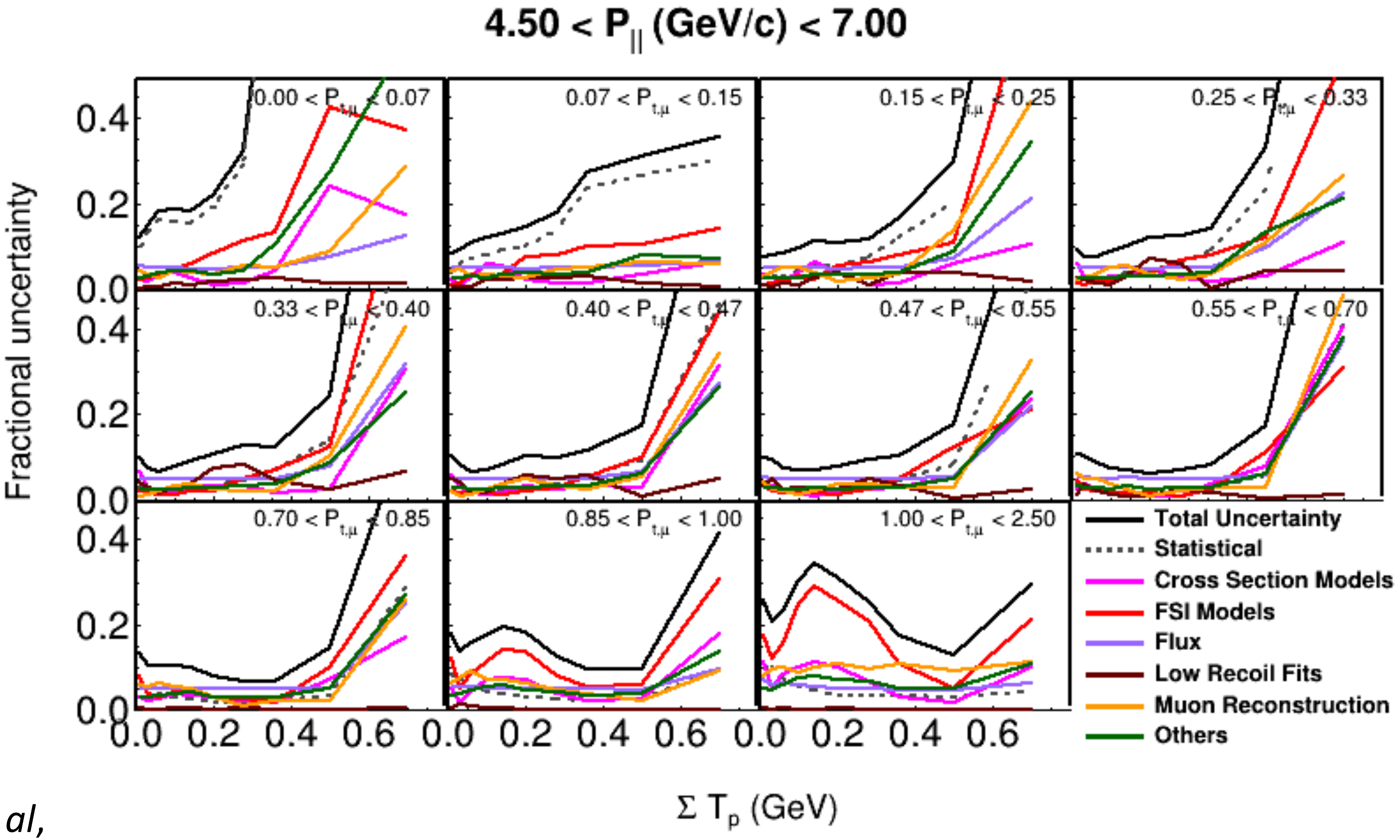
Charged Current 0π Cross Section Systematics



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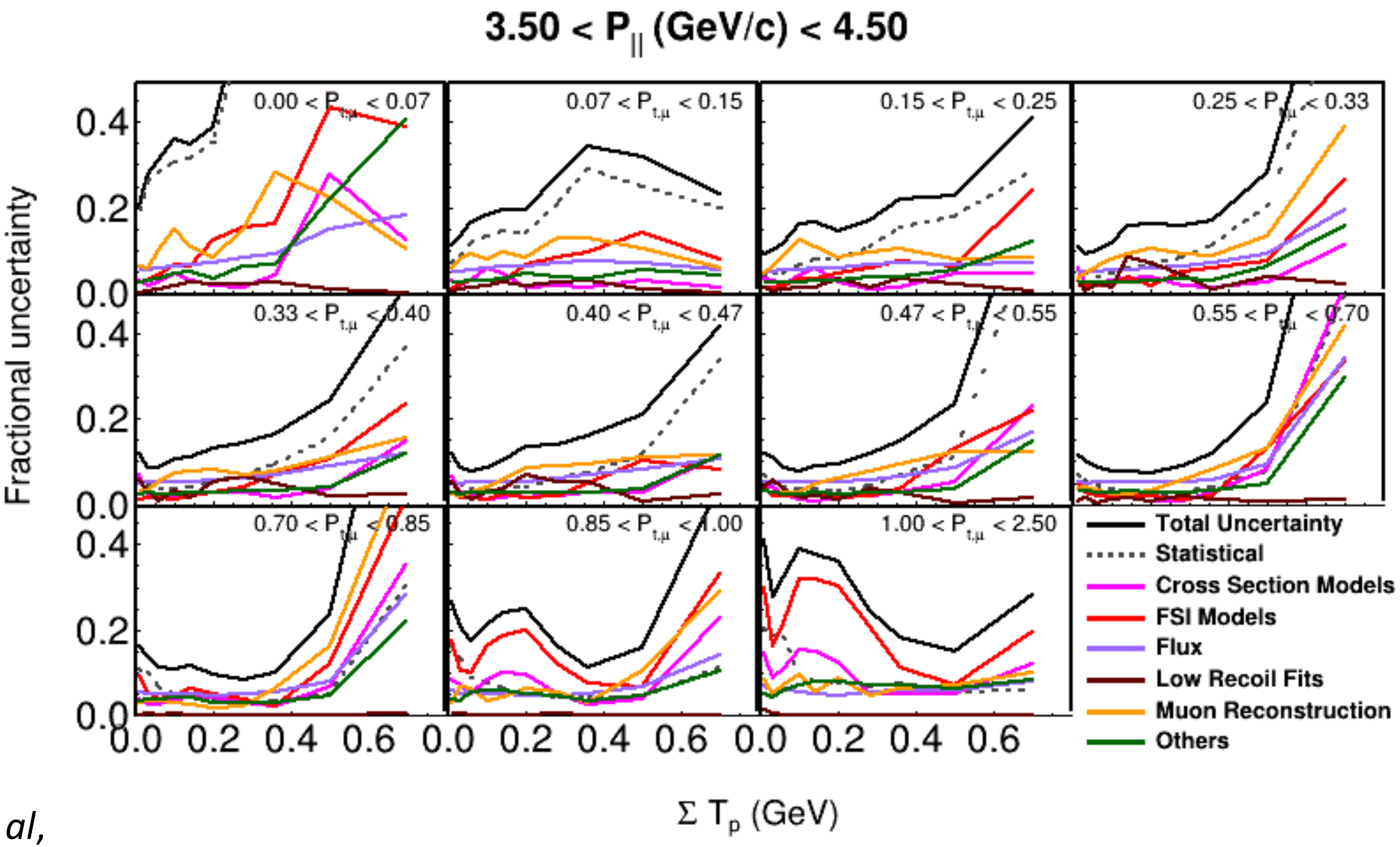

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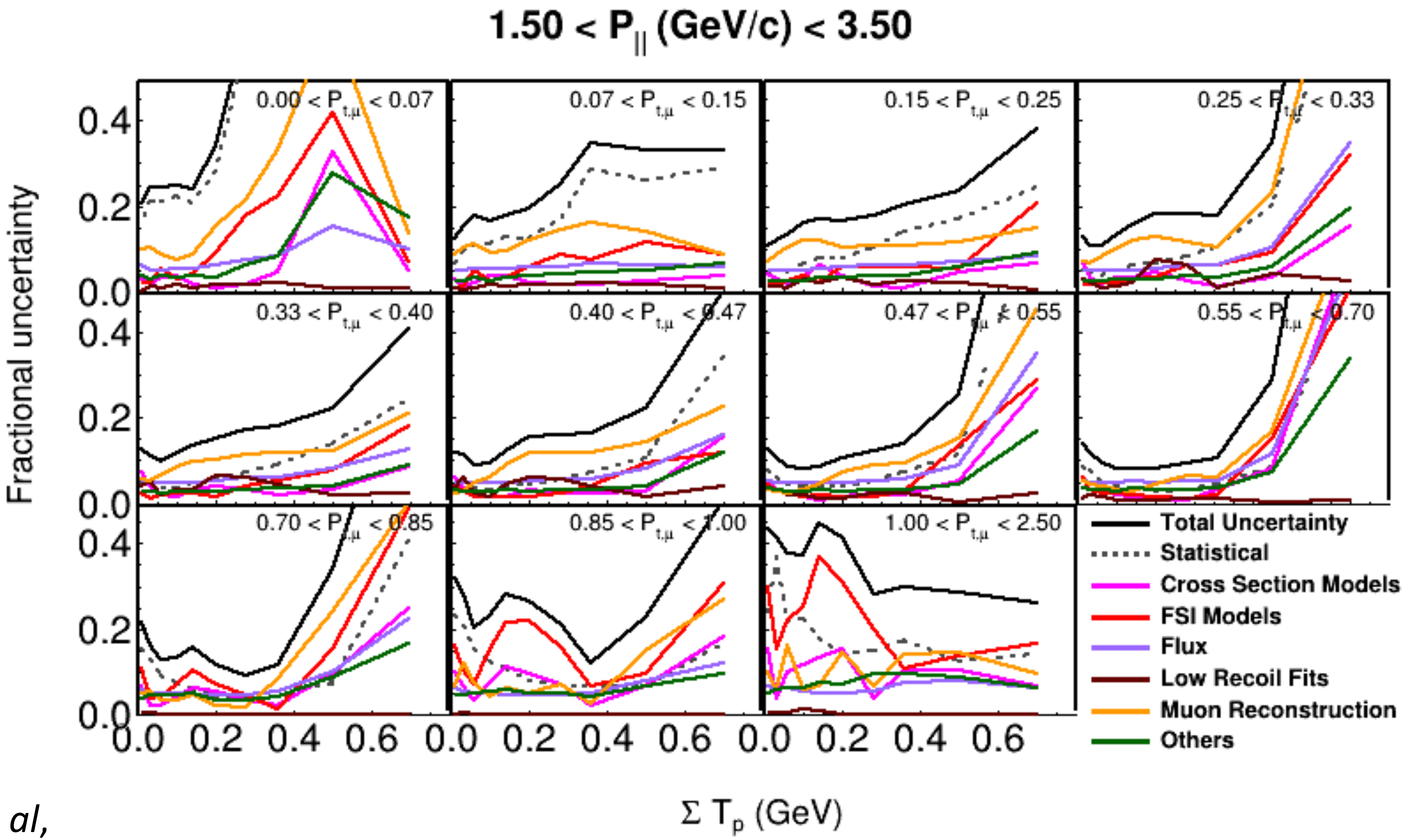

D. Ruterbories *et al*,
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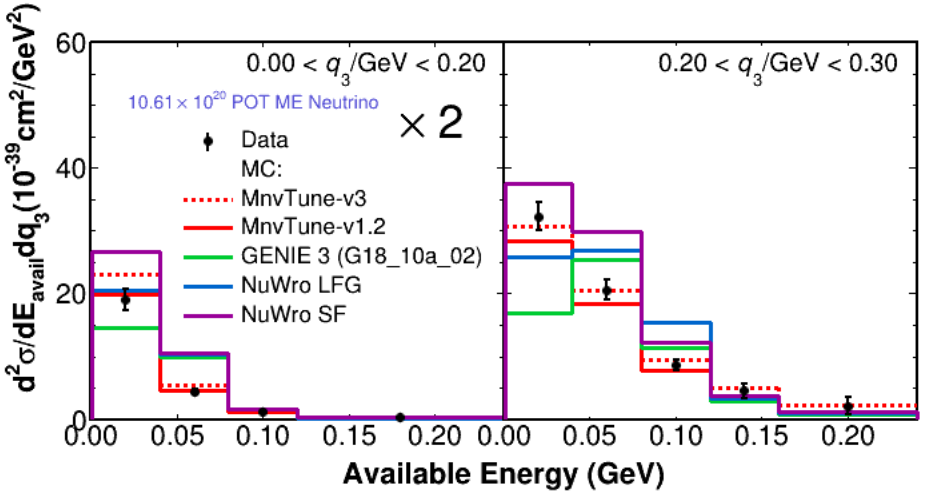
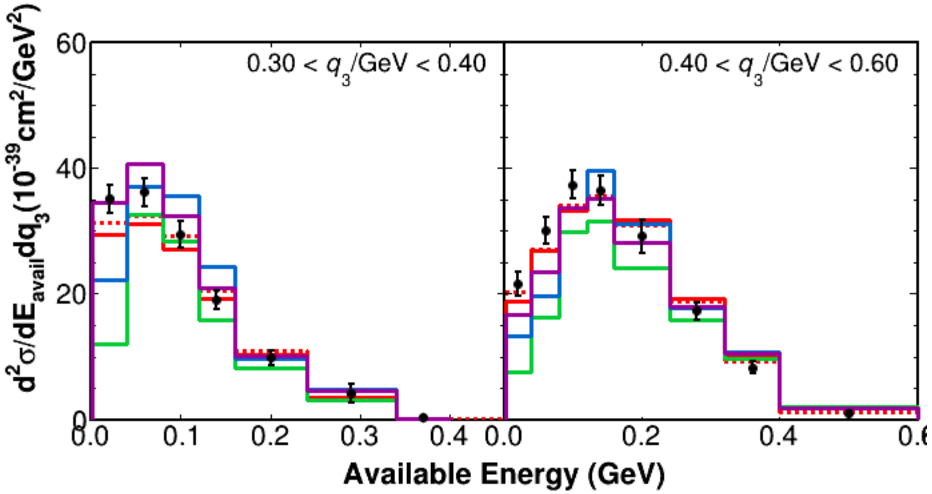
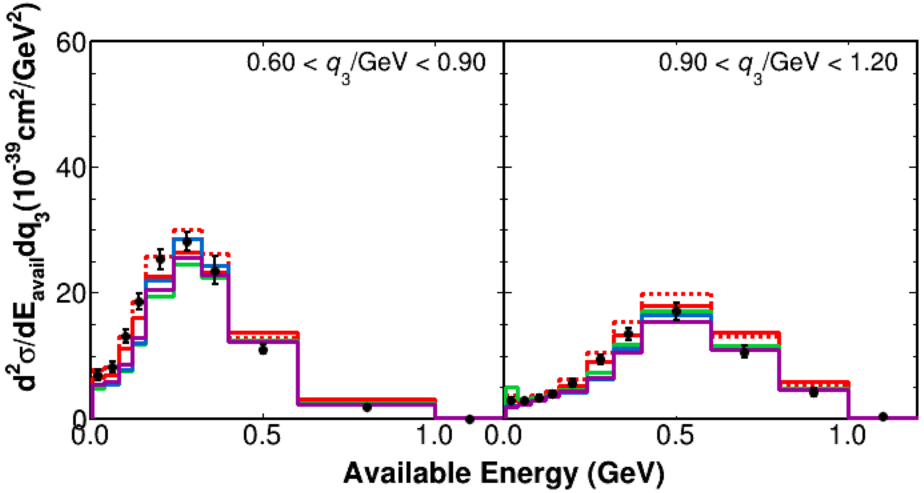
Inclusive Low q_3 Model Comparisons

- Several new models considered compared to previous results

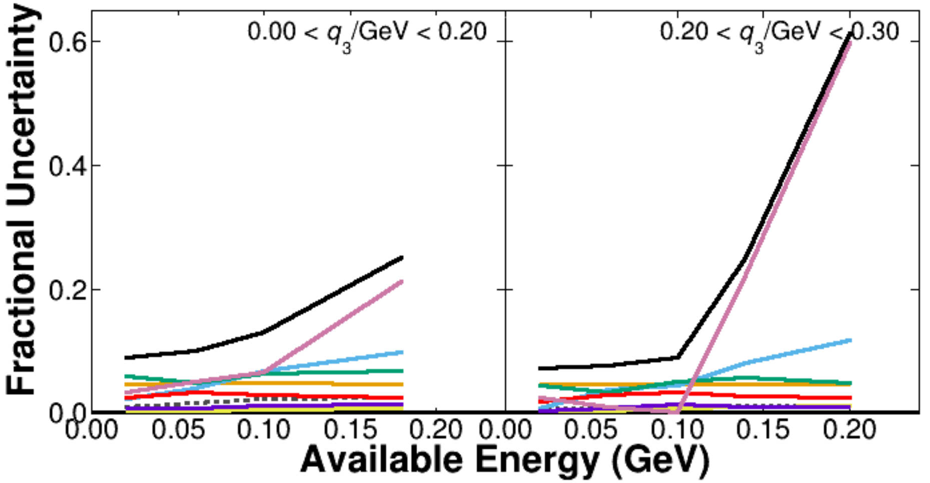


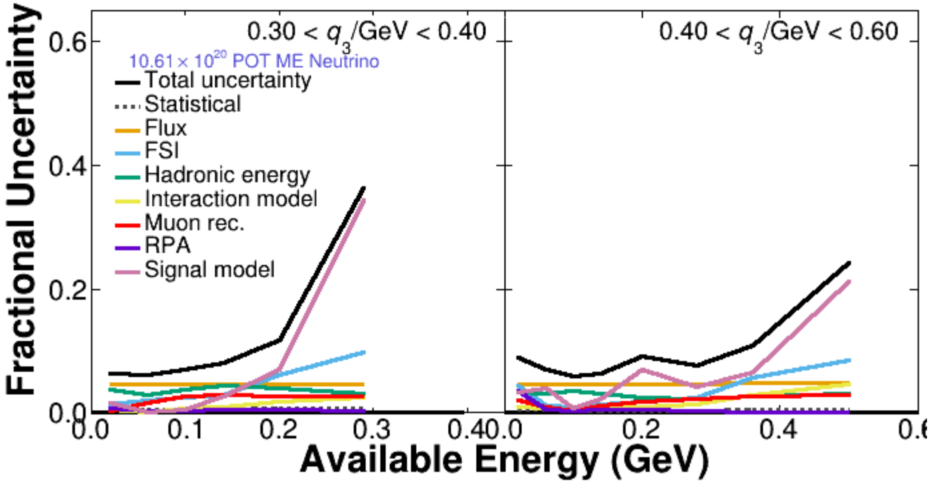
M. Ascencio et al, *Phys.Rev.D* 106 (2022) 3, 032001



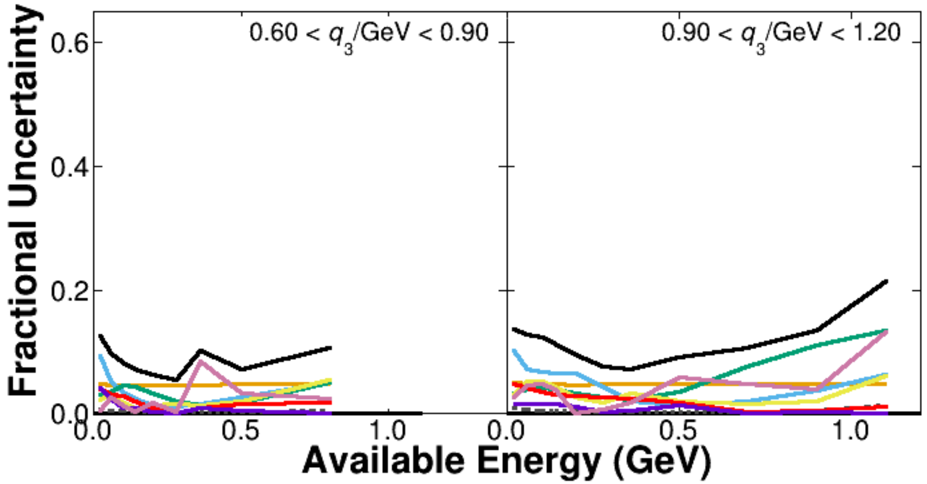


Inclusive Low q_3 Cross Section Uncertainties





- At low available energy, several uncertainties contribute,
- At high available energy, those associated with hadronic response dominate
- Marvin Ascencio et al, PRD…



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