Recent Neutrino-Induced Multipion Production Measurements

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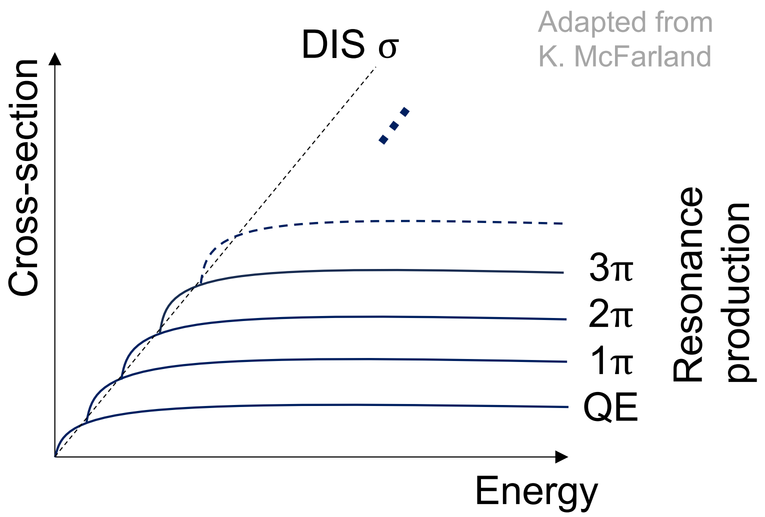
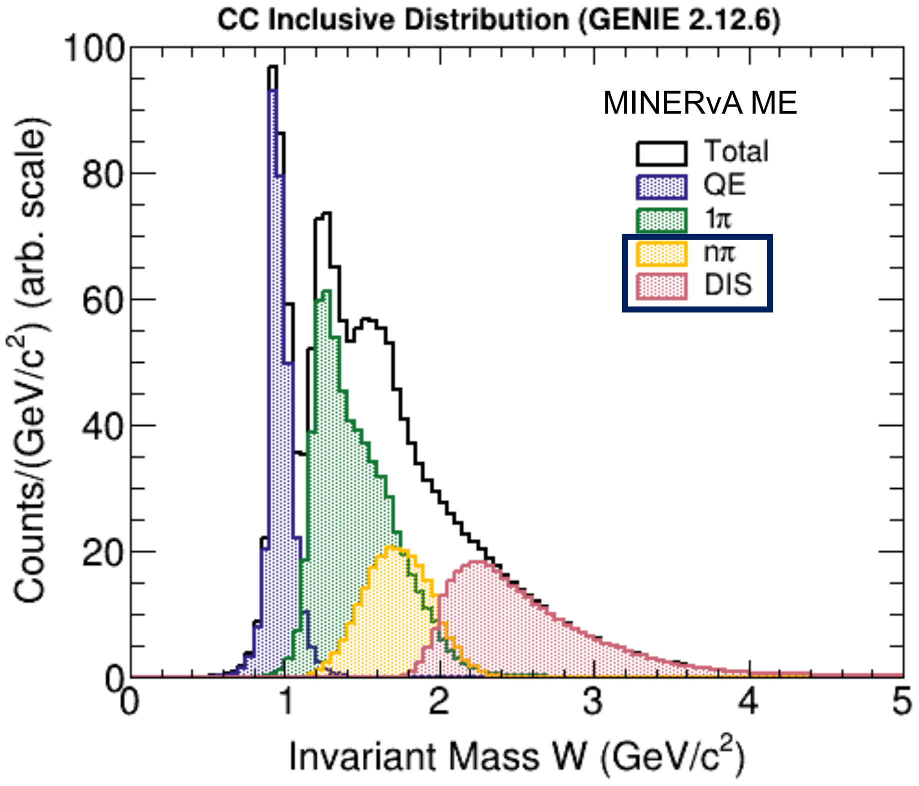
IMPERIAL

October 23rd, 2024
*Measuring Neutrino Interactions For Next-Generation Oscillation Experiments, ECT**

Multipion?

- (Anti)neutrino interactions producing 2+ pions in the final state – invariant mass $W \geq (m_{\mathrm{N}} + 2m_{\pi})$
- Contributions include:
  - Single pion production + FSI
  - Higher baryonic resonance decays
  - Non-resonant pion production
  - Transition region between the resonant region and deep inelastic scattering, i.e. shallow inelastic scattering (SIS)
  - Lower-energy deep inelastic scattering (DIS)
- Difficult to reconstruct multiple pion final states → **(semi)inclusive measurements in the relevant energy regime**





Why do we care?

Backgrounds of ~~today~~ yesterday becoming signals of ~~tomorrow~~ today…

- Future oscillation experiments DUNE and Hyper-Kamiokande will become systematics dominated

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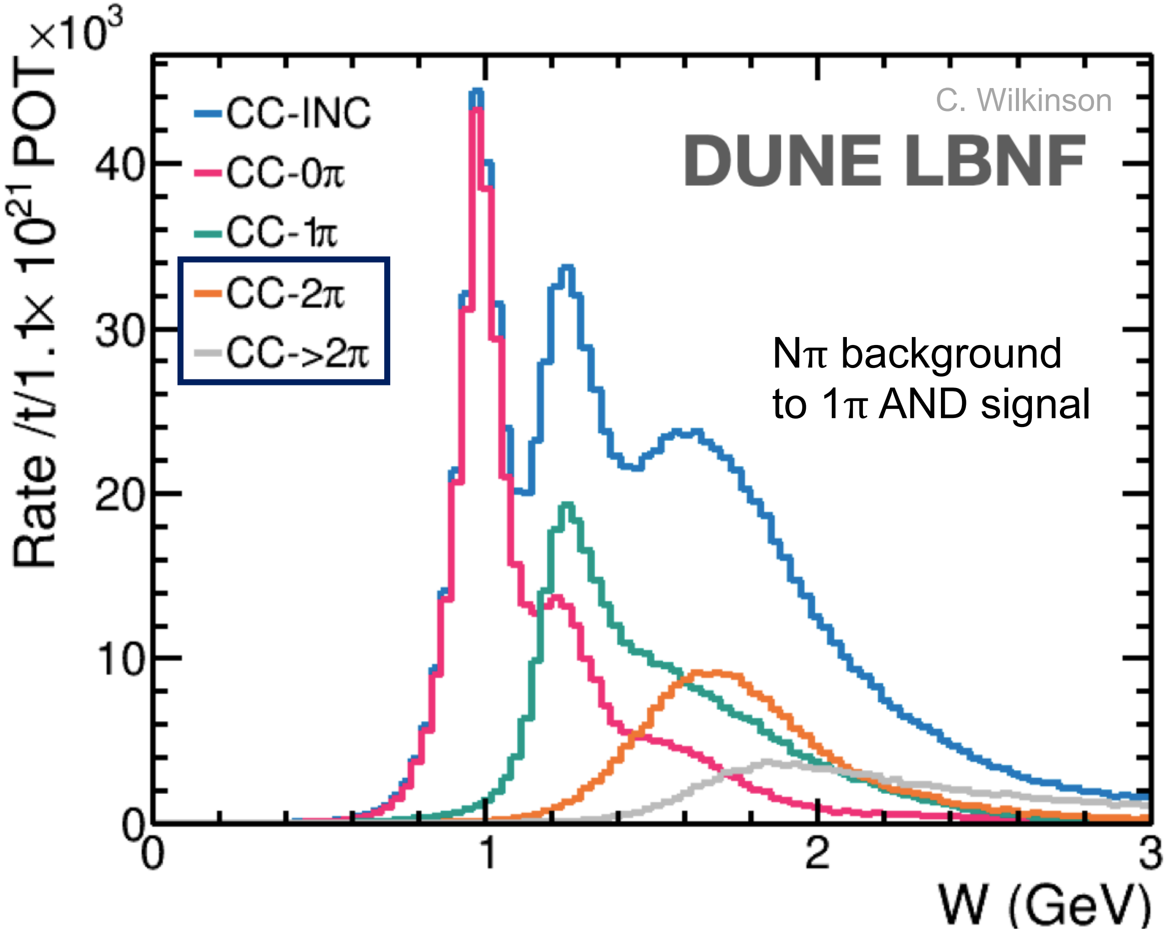
- **DUNE** will span complex region of phase space
  - Massive statistics @DUNE ND ~100 million events/year on argon
  - **Most events in DUNE will contain a pion**
  - 45% of ν_μ CC events will have $W \geq 1.5$ GeV



Why do we care?

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Hyper-Kamiokande

Backgrounds of ~~today~~ yesterday becoming signals of ~~tomorrow~~ today…

5.4.2.5 Other hard scattering uncertainties

DUNE TDR

NOvA oscillation analyses [171] have found the need for excursions beyond the default GENIE uncertainties to describe their single pion to deep inelastic scattering (DIS) transition region data. Following suit, we drop GENIE's default "Rv[n,p][1,2]pi" knobs and instead implement separate, uncorrelated uncertainties for all perturbations of 1, 2, and ≥ 3 pion final states, CC/NC, neutrinos/anti-neutrinos, and interactions on protons/neutrons, with the exception of CC neutrino 1-pion production, where interactions on protons and neutrons are merged, following [166]. This leads to 23 distinct uncertainty channels ([3 pion states] x [n,p] x [nu/anti-nu] x [CC/NC] - 1), all with a value of 50% for $W \leq 3$ GeV. For each channel, the uncertainty drops linearly above $W = 3$ GeV until it reaches a flat value of 5% at $W = 5$ GeV, where external measurements better constrain this process.

+ FSI…

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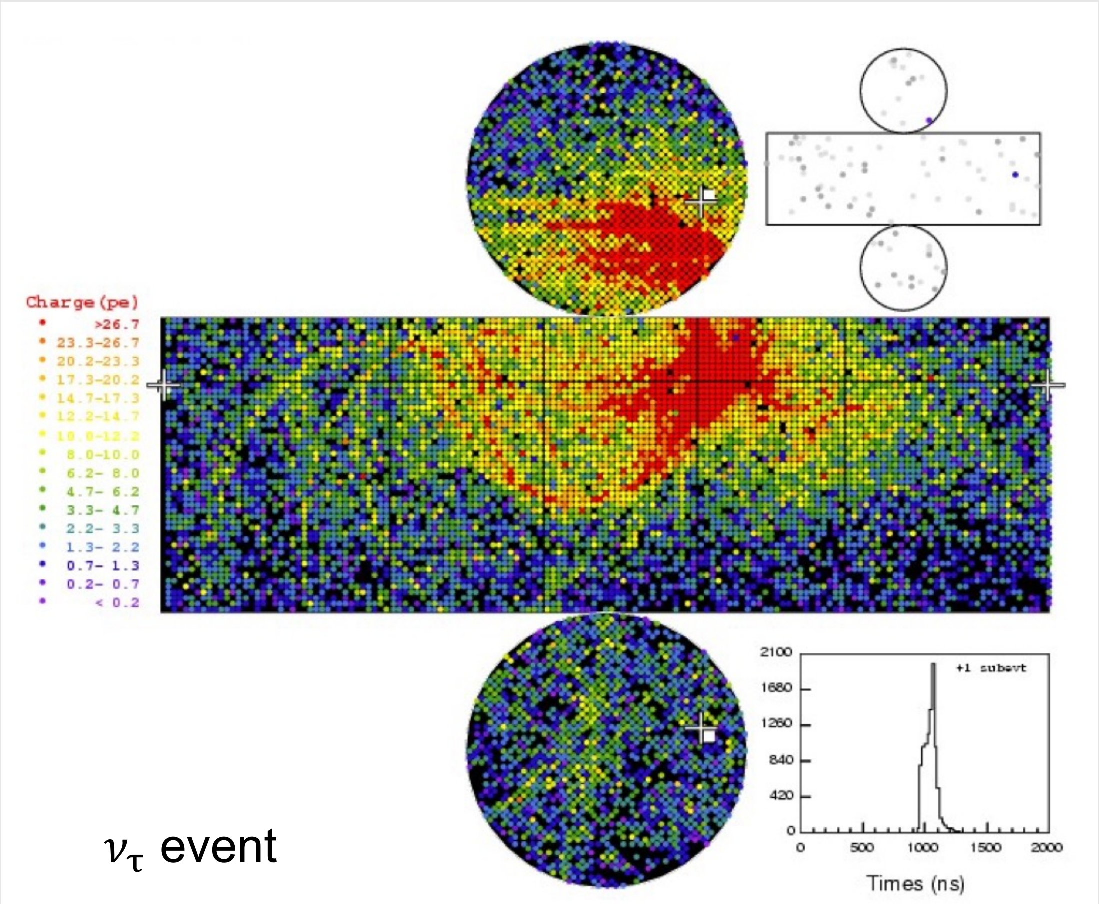
- **In Hyper-Kamiokande**, important for the atmospheric samples
  - Sensitive to mass ordering via 3-10 GeV region
  - Primary lepton ring hard to reconstruct in DIS events
  - Confused with ν_τ appearance events

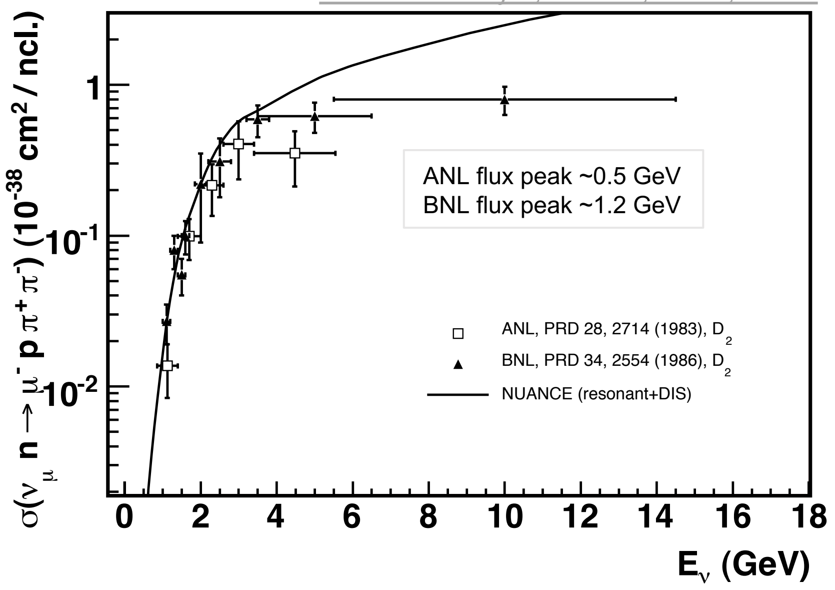


R. Wendell, NuInt15

Experiments in the relevant energy regime

Rev. Mod. Phys., Vol. 84, No. 3, 2012

- **Bubble chambers** – di-pion production measurements on D_2



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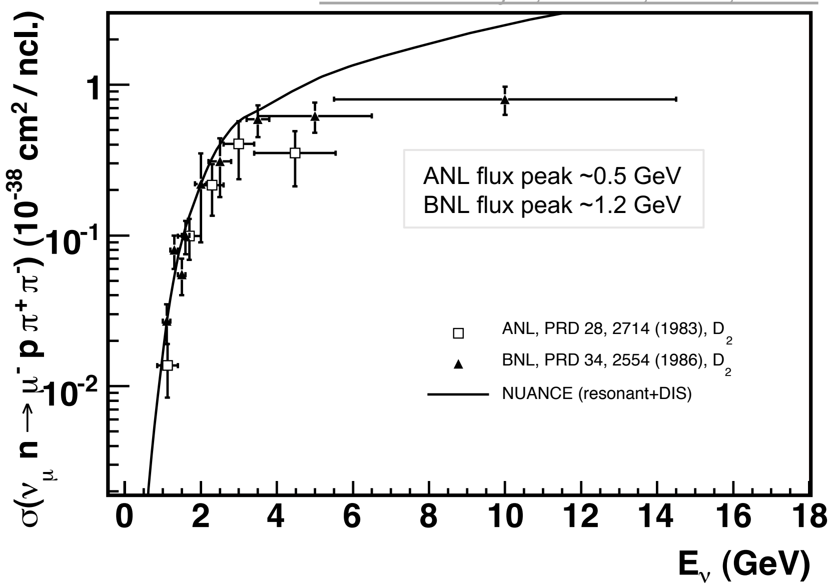
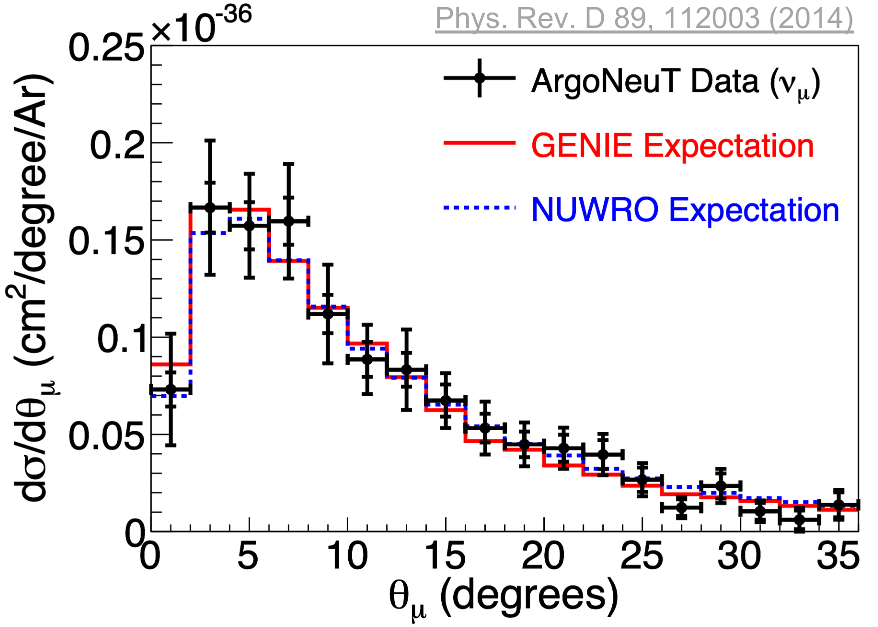


Phys. Rev. D 89, 112003 (2014)



Flux peak ~9.6 GeV ν_μ (~3.6 GeV $\bar{\nu}_\mu$)

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- **NOvA** – inclusive, and semi-inclusive pion measurements on liquid scintillator (67% C, 16% Cl_2, 11% H_2, some Ti, O_2)
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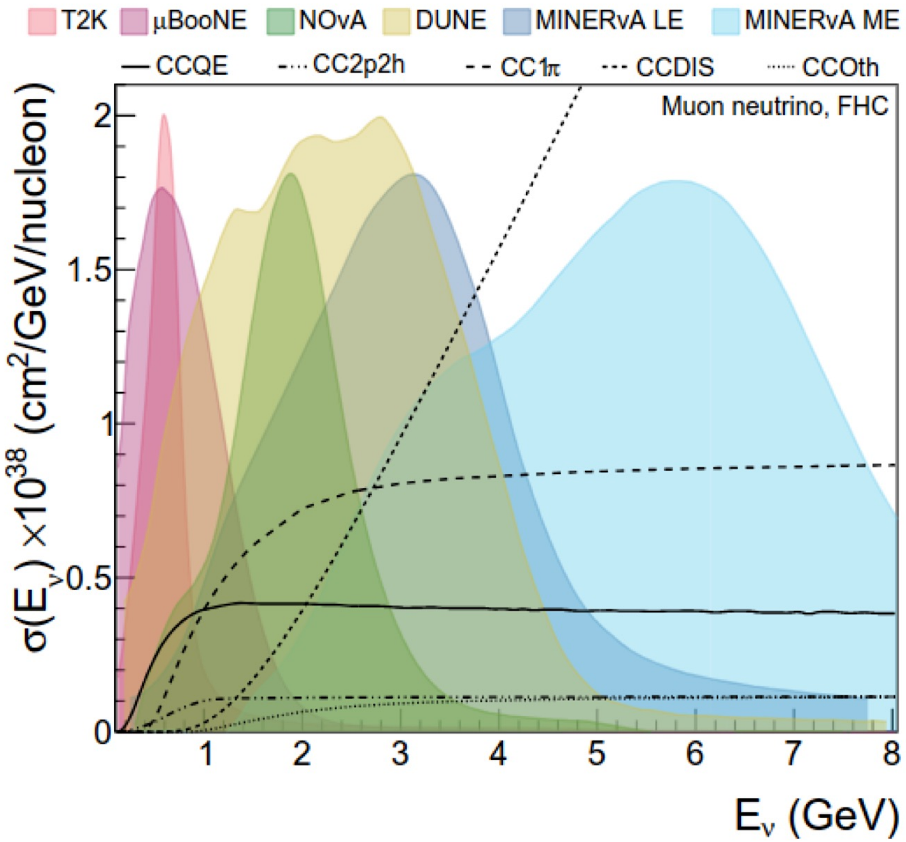
C. Wret, NuInt2024



Region of interest

NOvA flux peak ~2 GeV
MINERvA LE flux peak ~3 GeV
MINERvA ME flux peak ~6 GeV

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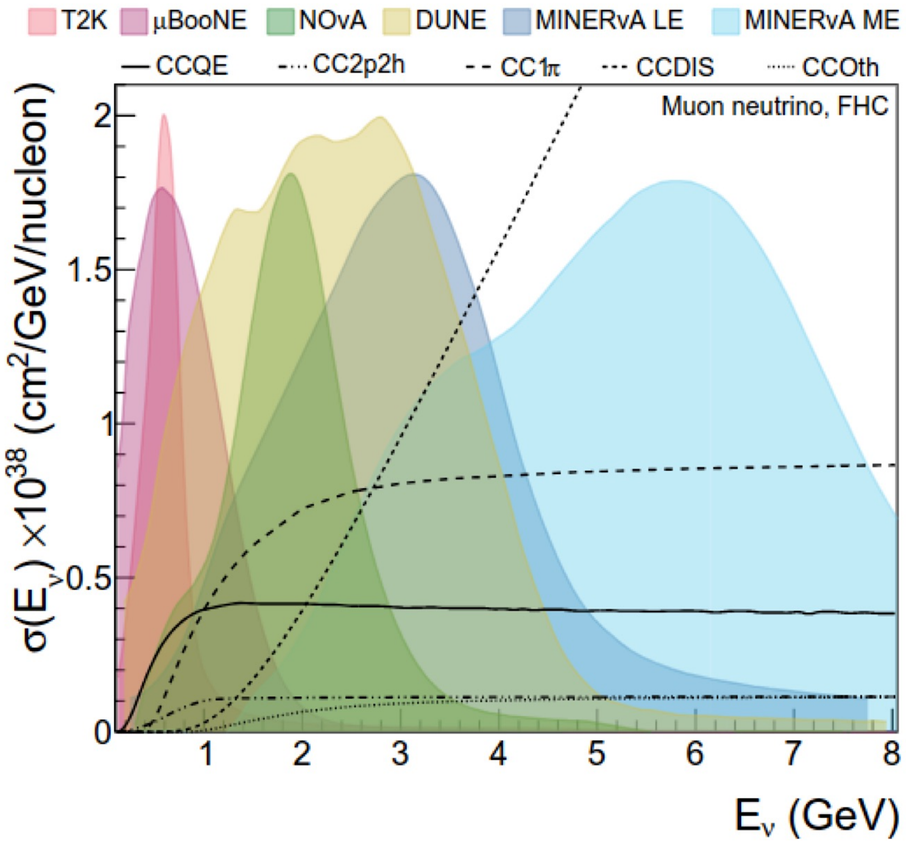

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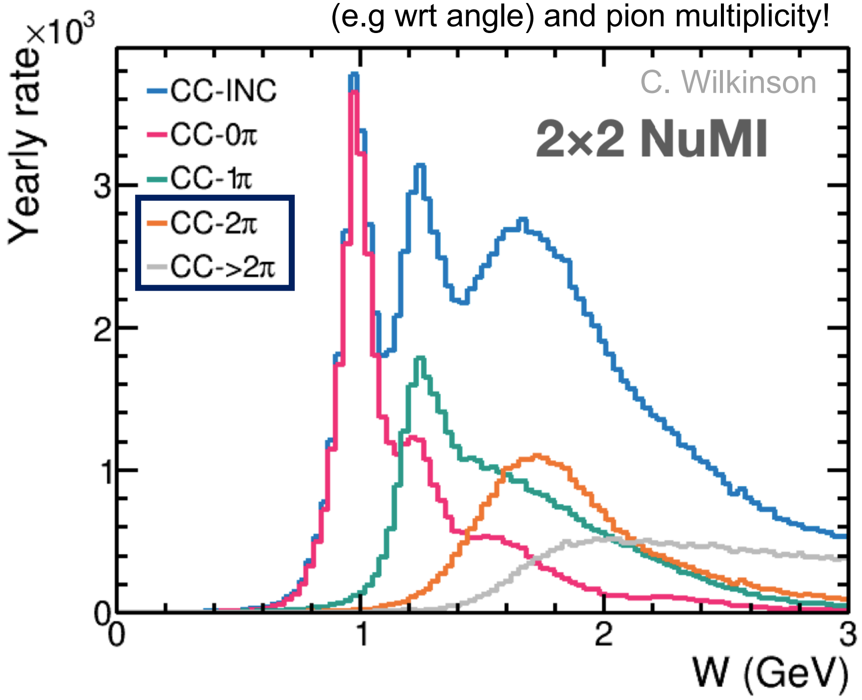
Should be able to do inclusive measurements (e.g wrt angle) and pion multiplicity!



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- *Near future:* 2x2 demonstrator (ND-LAr + MINERvA tracker) in the NuMI beamline (flux peak ~6 GeV)

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Focus! Recent measurements!

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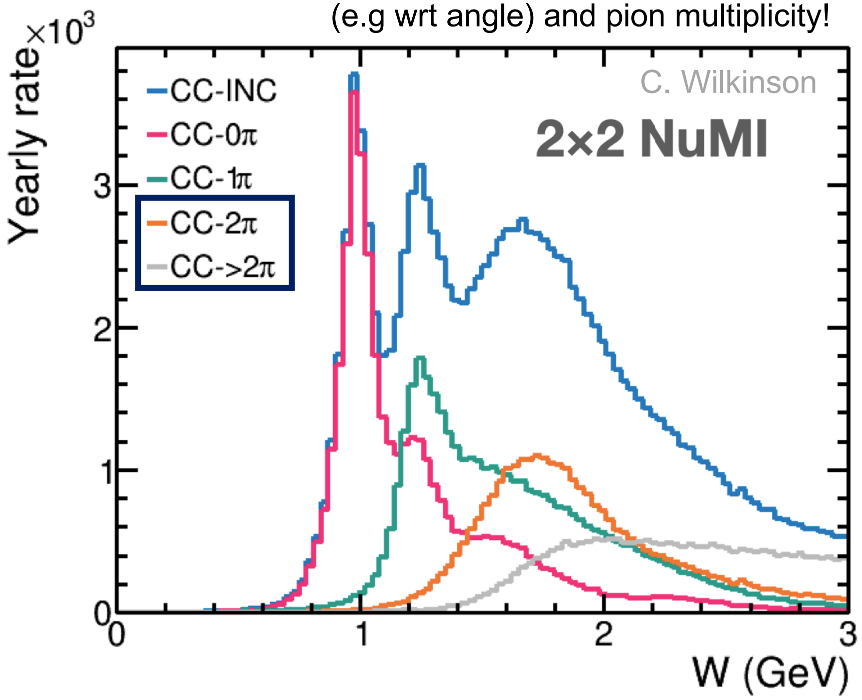

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(Recent) measurements

2024

More exclusive

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"Older" measurements

MINERvA LE (~3.5 GeV)

1D ν_μ inclusive vs A (2014)

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NOvA's inclusive measurement(s)

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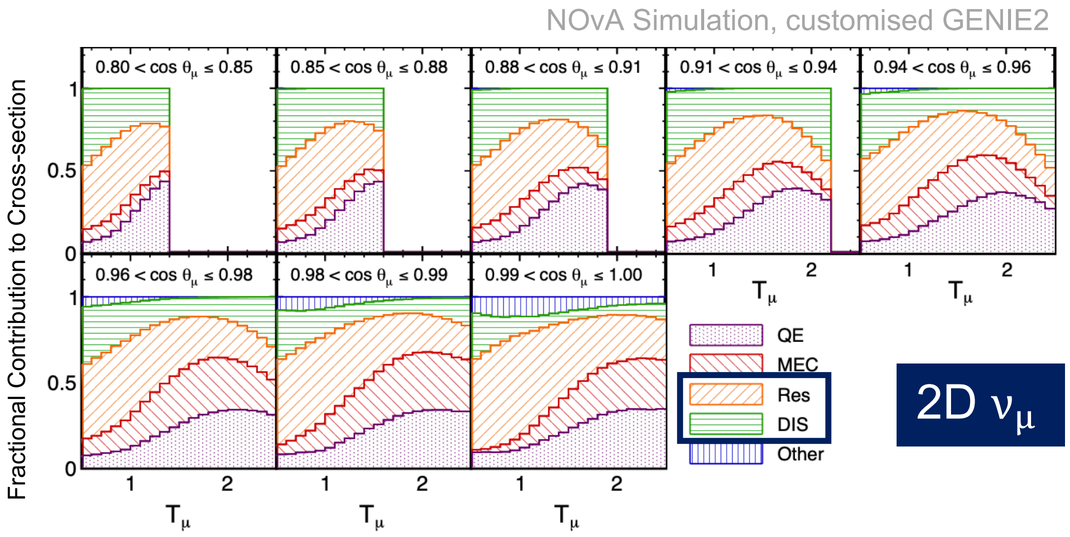
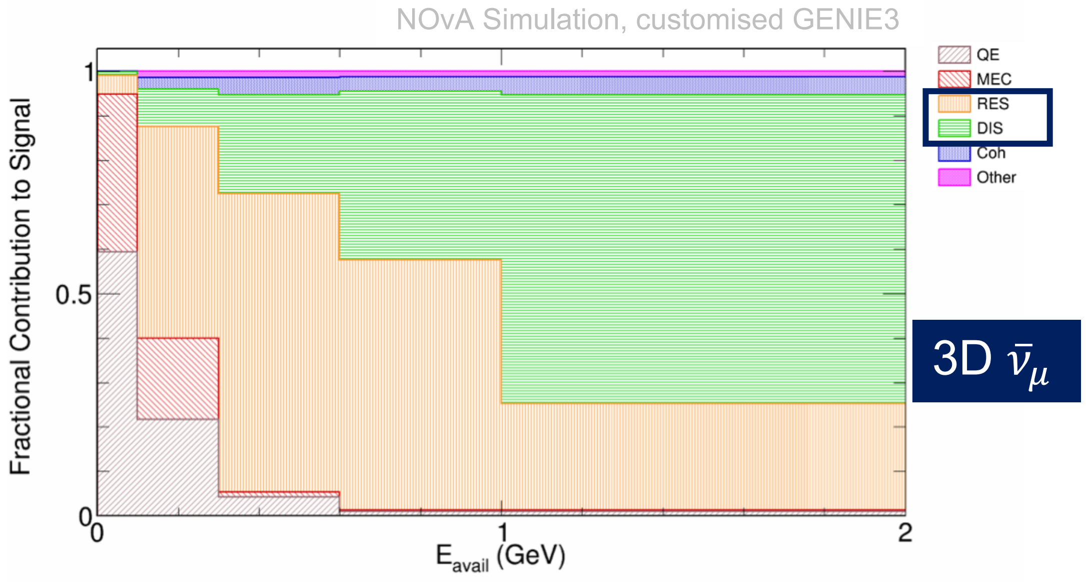
- 2D neutrino (T_μ, $\cos\theta_\mu$), 3D antineutrino (T_μ, $\cos\theta_\mu$, E_{avail})
- Flux peak ~2 GeV, expected significant contribution from Nπ – lower T_μ and higher E_{avail}



2D ν_μ



3D $\bar{\nu}_\mu$

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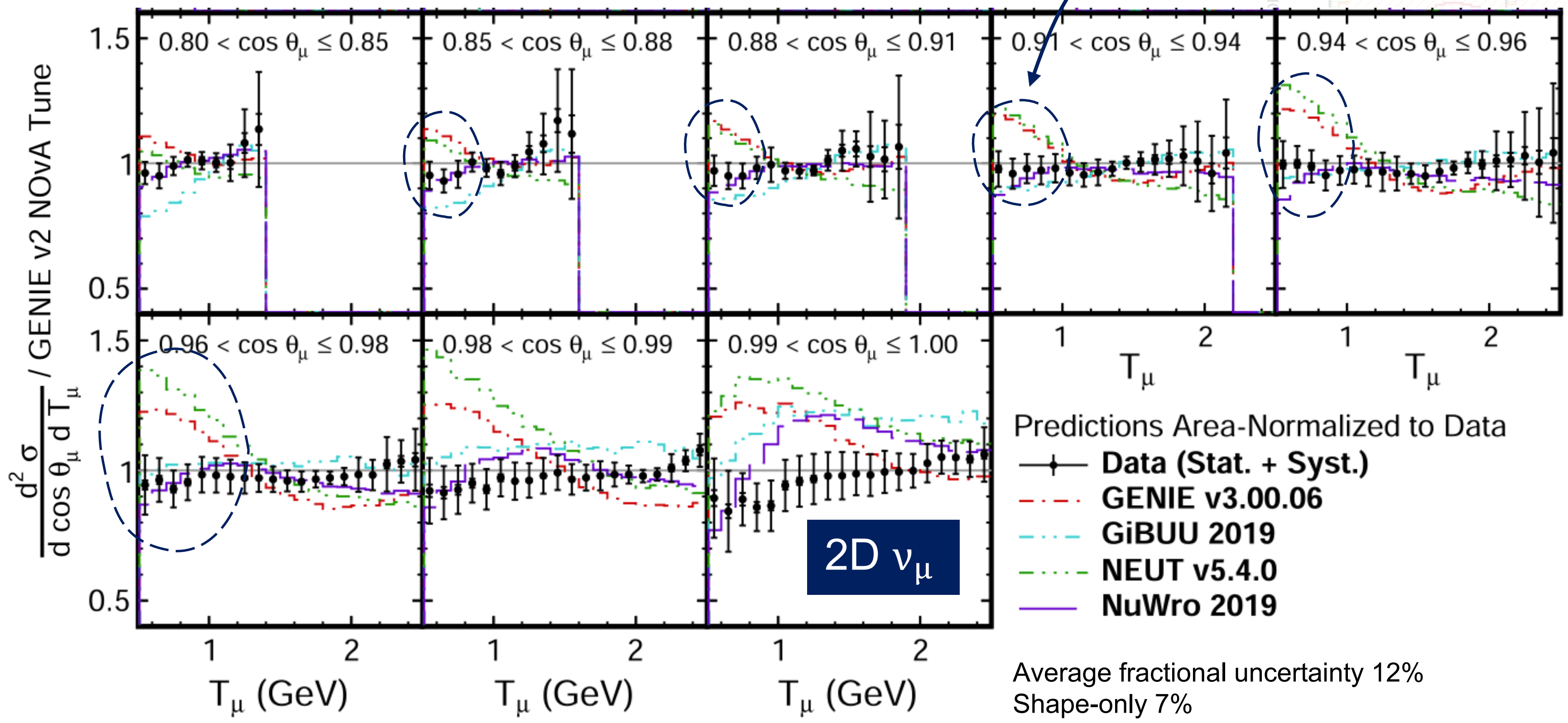
GENIE3 and NEUT overpredict the data for forward-going low T_μ muons



Average fractional uncertainty 12%
Shape-only 7%

Surprisingly (?) NOvA's customised GENIE2 seems to model the data well

Where does this overprediction come from?

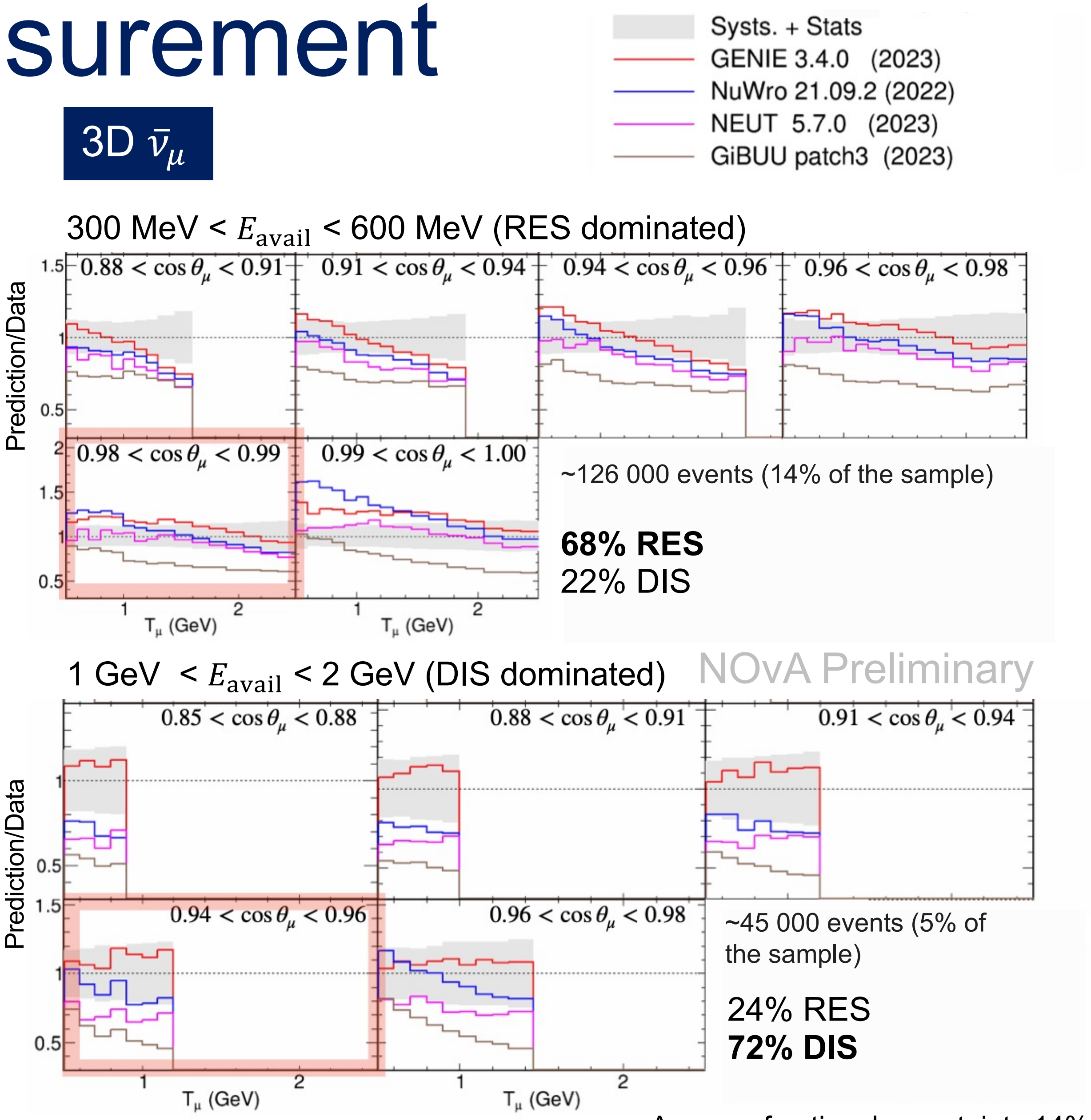
Look into the 3D!

NOvA's inclusive measurement

P. Singh, Wine&Cheese, 2024

3D $\bar{\nu}_\mu$

- E_{avail} slices powerful to localise problems in modelling
- Antineutrino, but like in ν, GENIE3 overprediction at lower T_μ and higher $\cos\theta_\mu$
  - In the RES (and RES→DIS transition) rather than in the DIS dominated
- Some variation in the RES dominated region, NEUT close to the data at low T_μ and higher $\cos\theta_\mu$
- Different FSI and transition hadronisation with Bodek-Yang in the DIS dominated region (except GiBUU) – GENIE3 seems to model the data the best



Average fractional uncertainty 14%

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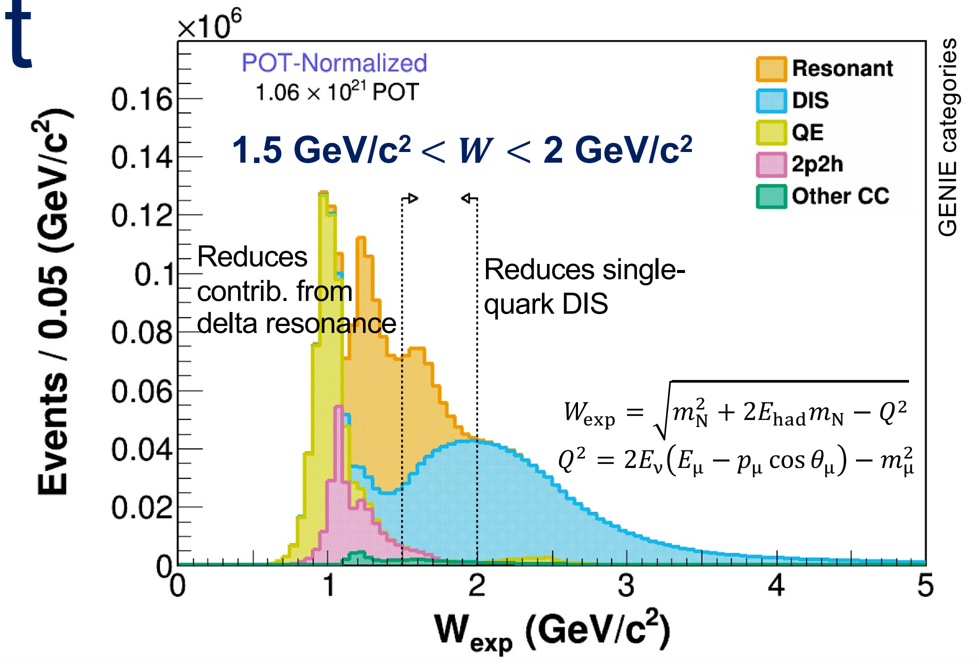
MINERvA's SIS measurement

- 1D neutrino and antineutrino cross-sections reported in (anti)muon momentum variables and variables sensitive to the hadronic system
- Calorimetric reconstruction of visible recoil energy with model-dependent correction for invisible energy
- QE, resonant, and higher W DIS background constraint in sideband regions via simultaneous shape+normalisation fit to data



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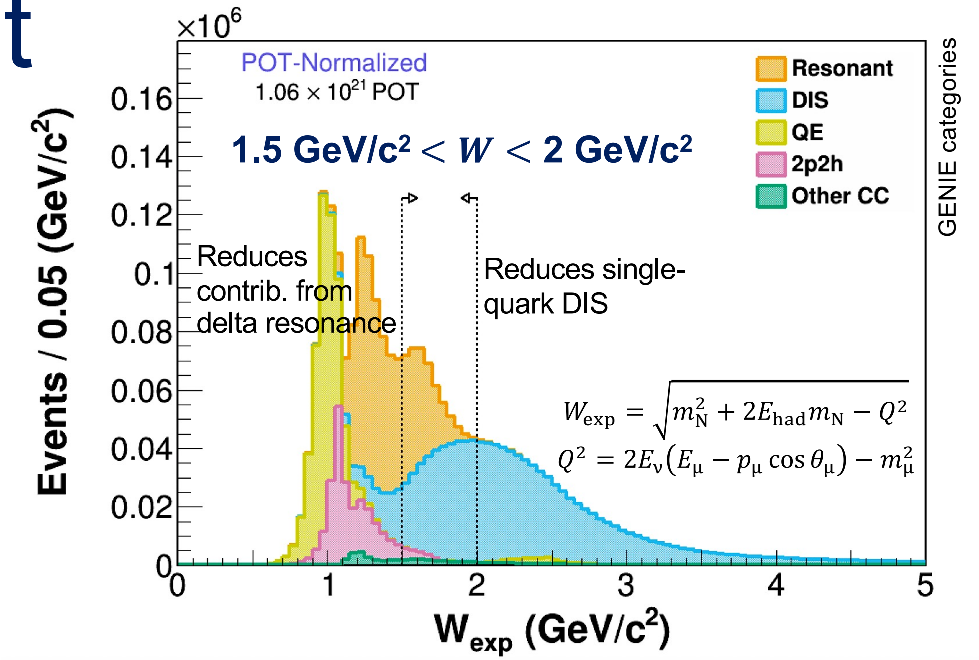
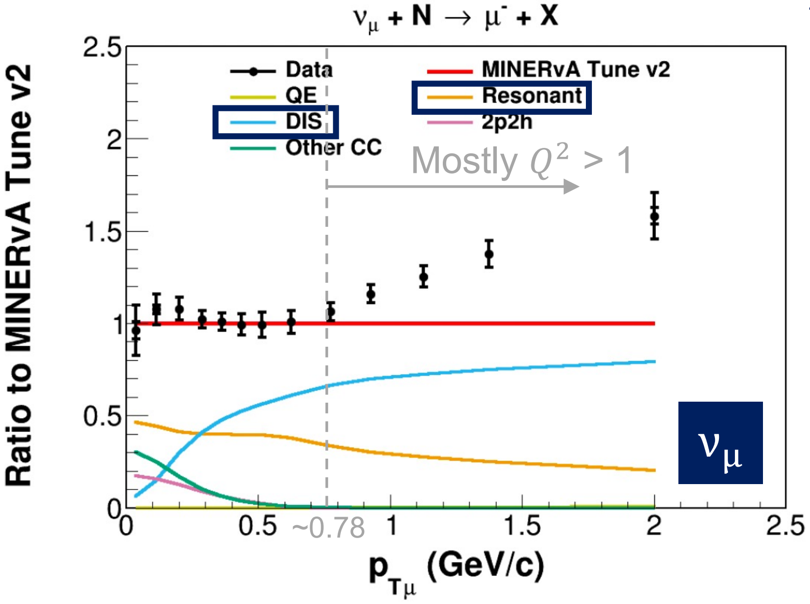
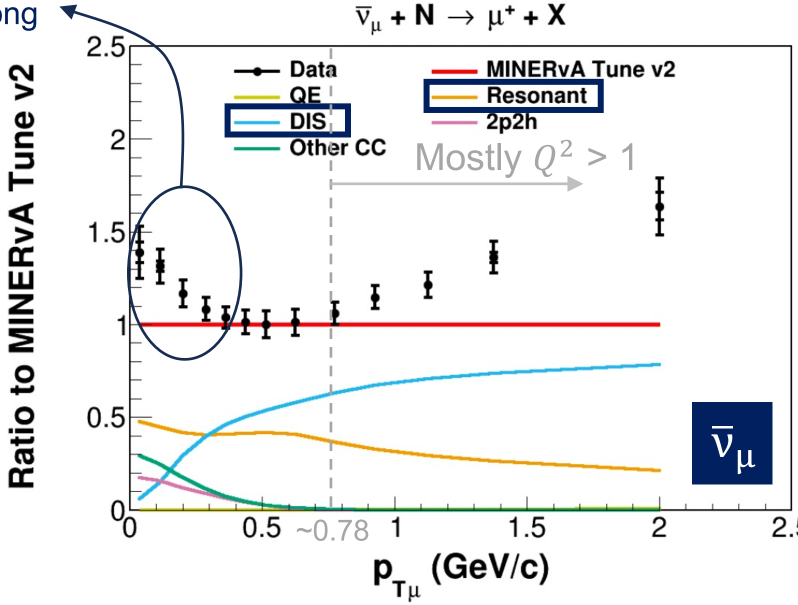


Low Q^2 suppression too strong





High $p_{T\mu}$ underprediction, shape not quite right (true SIS region with $Q^2 > 1$)

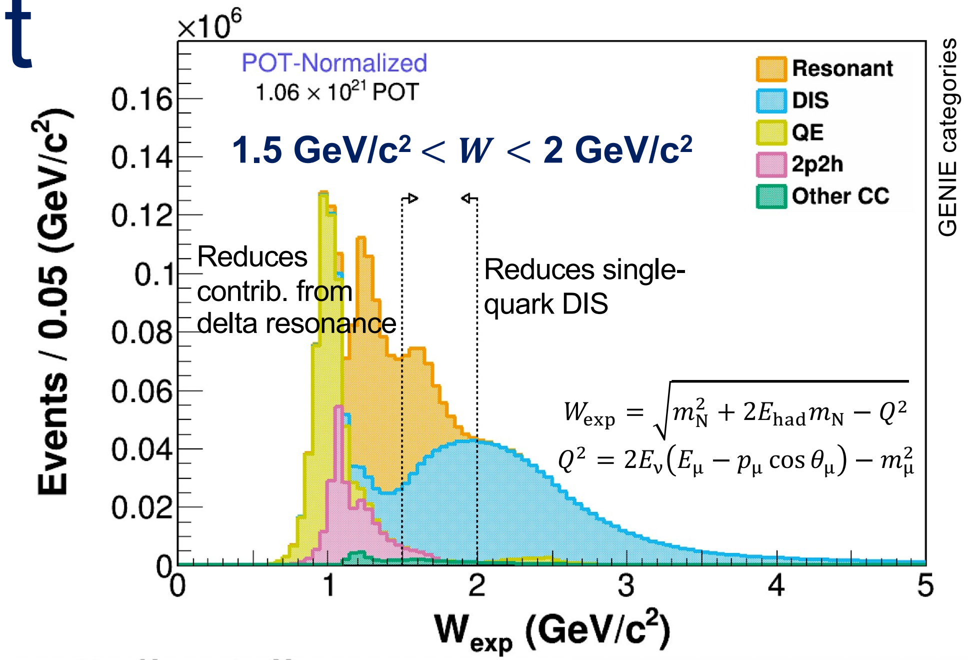
Uncertainties dominated by flux, interaction model ($M_{A/V}^{RES}$), and detector response

$$Q^2 \approx p_T^2\left(1 + \mathcal{O}\left(\frac{E_{recoil}}{E_\mu}\right)\right)$$

ME datasets
2 GeV $< E_\mu <$ 20 GeV

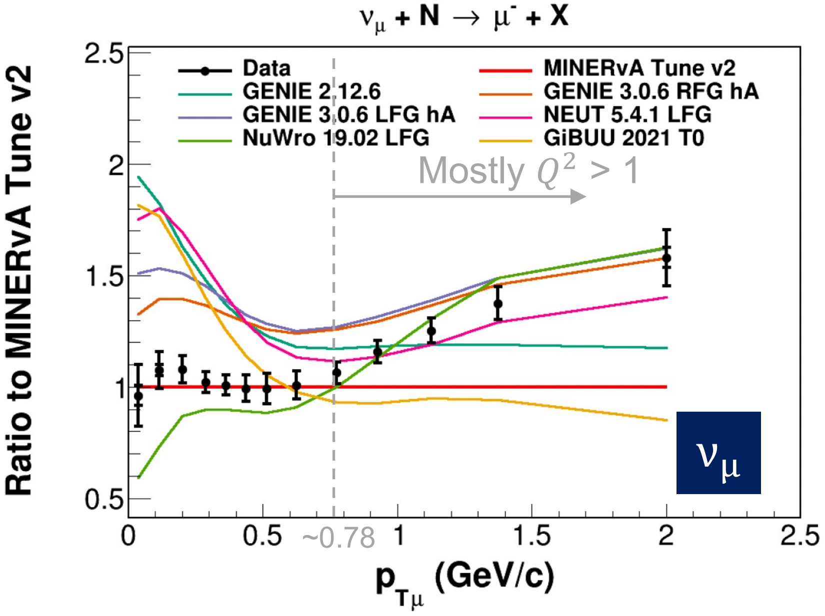
MINERvA's SIS measurement

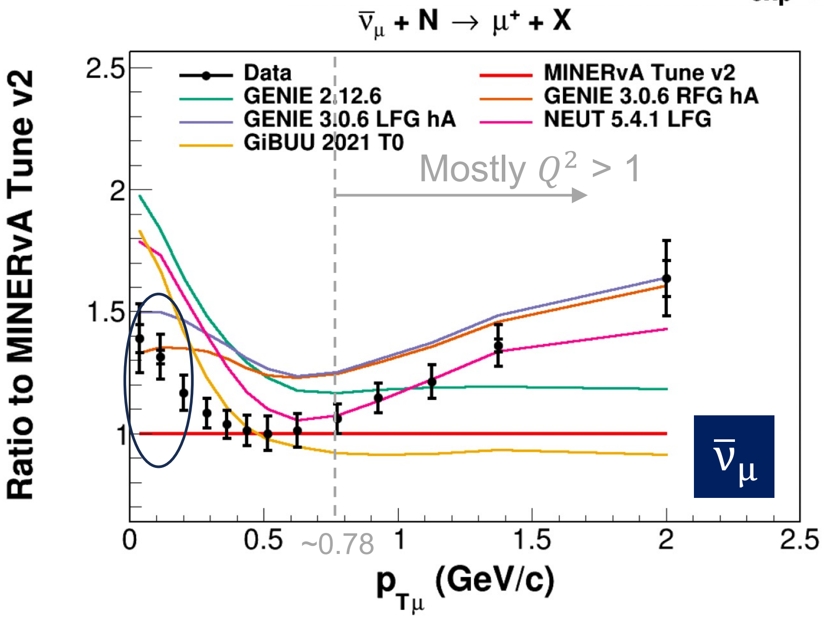
- None of them describe data well across the full kinematic region
- At low $p_{T\mu}$ central value does pretty well
- At high $p_{T\mu}$ GENIE3 gets shape right, NuWro and NEUT fit well
- Other variables, dedicated $Q^2 > 1$ GeV^2 analysis for multi-quark component of SIS, full systematics info in the publication



$$W_{exp} = \sqrt{m_N^2 + 2E_{had}m_N - Q^2}$$

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





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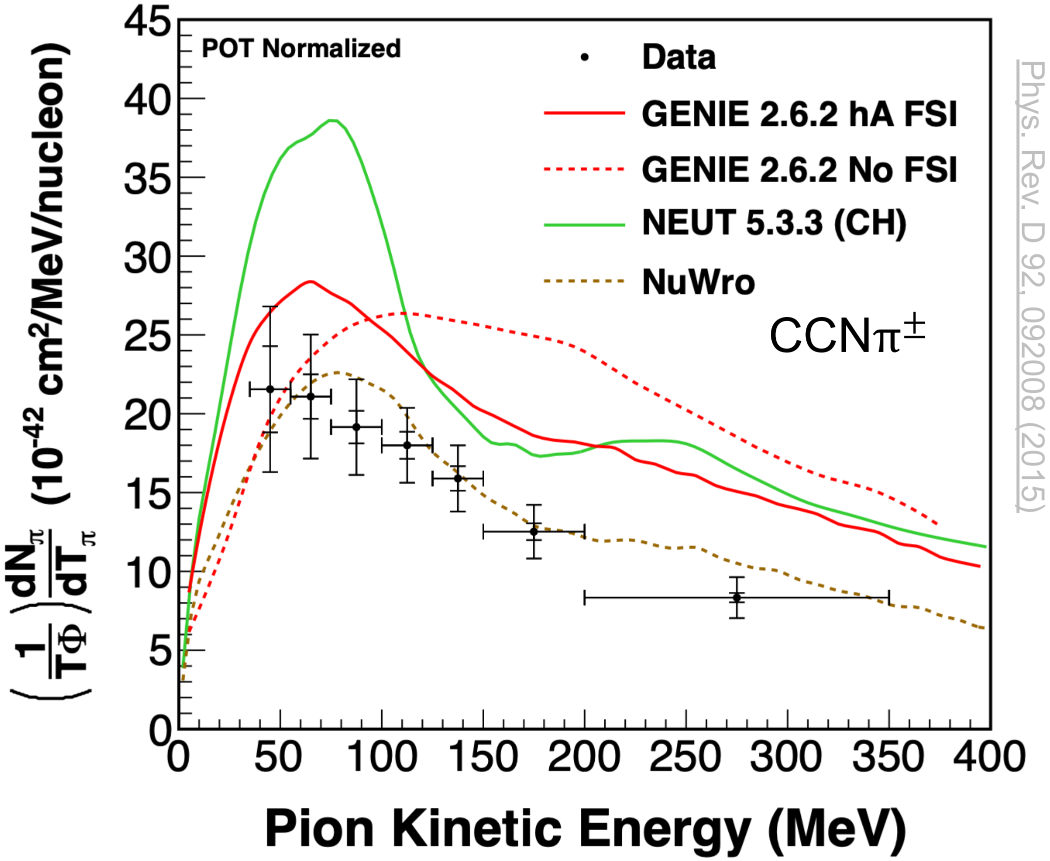


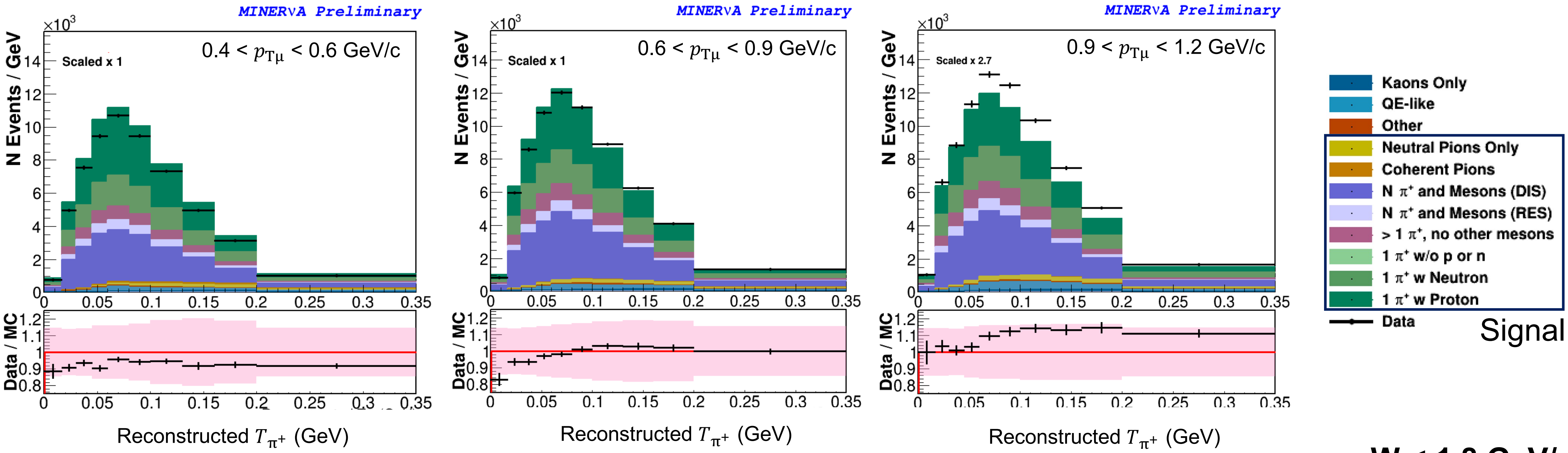
Phys. Rev. D 92, 092008 (2015)

Not the first time $W < 1.8$ GeV!

LE vs ME, 1D vs 2D, tuned GENIE 2.6.2 vs tuned GENIE 2.12.6

MINERvA's CC ν_μ $\geq 1\pi^+$

- Extended π^+ momentum reach, including pions only found through Michel tag (unconstrainted kinematic region, model tuned to get more realistic smearing, see Deborah's talk)
- Significant $N\pi^+$contribution at higher $p_{T\mu}$ – transition from RES to SIS to DIS

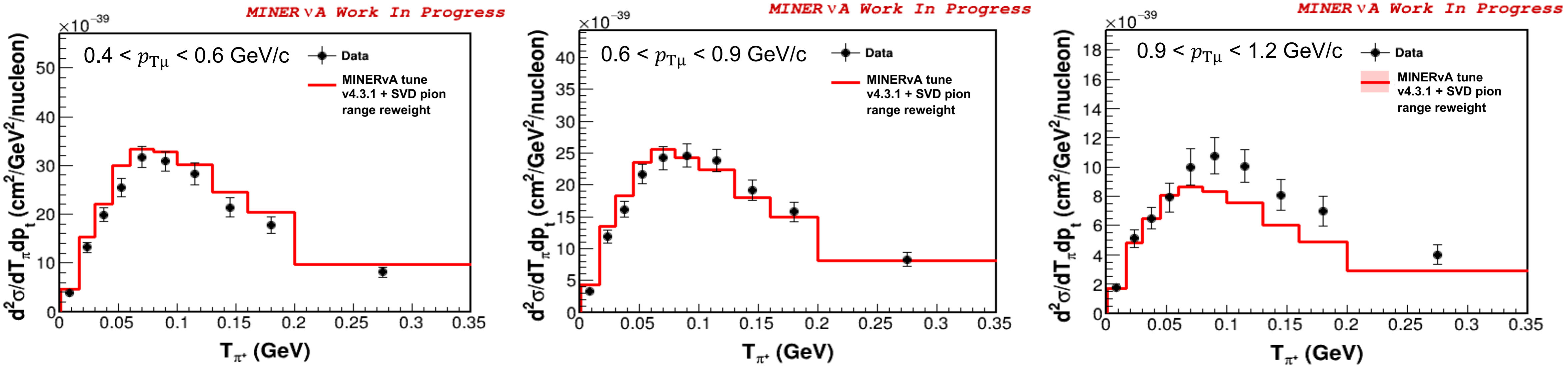


W < 1.8 GeV/c²

D. Harris for M. Sultana, NuInt2024

MINERvA's CC $\nu_\mu \geq 1\pi^+$

- Clear peak shift from low $p_{T\mu}$ to high $p_{T\mu}$
- Underprediction at high $p_{T\mu}$
- Similar behaviour as the SIS measurement



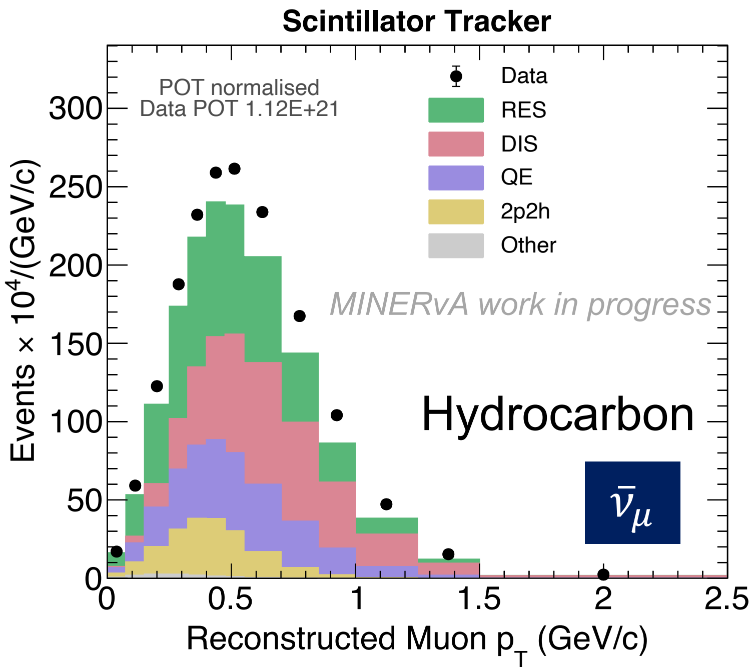
W < 1.8 GeV/c²

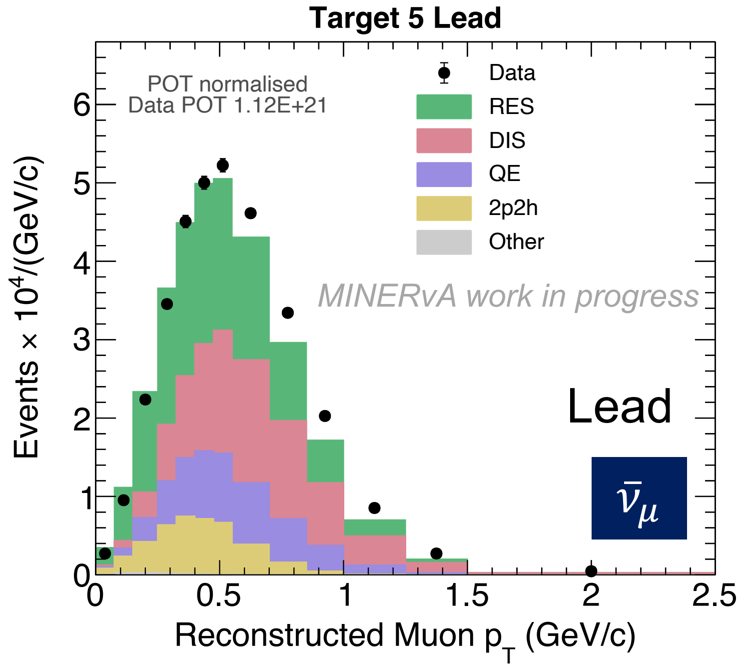
Final thoughts (1)

- MINERvA and NOvA probe multipion production via inclusive and semi-inclusive measurements – complex contributions from multiple interaction channels
- Dimensionality and correlation with recoil help localise problems
- Highly tuned central values often perform well, need to be cautious of model dependence
- Model variation in the $\mathrm{N}\pi$ region from FSI and transition hadronisation
- Focused on low $p_{\mathrm{T}\mu}$ and high $p_{\mathrm{T}\mu}$ behaviour – indication of missing low $p_{\mathrm{T}\mu}$ (Q^2) suppression across the board in the RES→SIS→DIS transition at least in GENIE3 models

Final thoughts (2)

- Getting cross-section results into NUISANCE for comprehensive quantitative comparison is crucial
- Data preservation – future models can be benchmarked against these measurements
- More measurements in preparation – inclusive and DIS vs *A* in 1D and 2D, 2D SIS both in neutrino and antineutrino





Final (final) thoughts

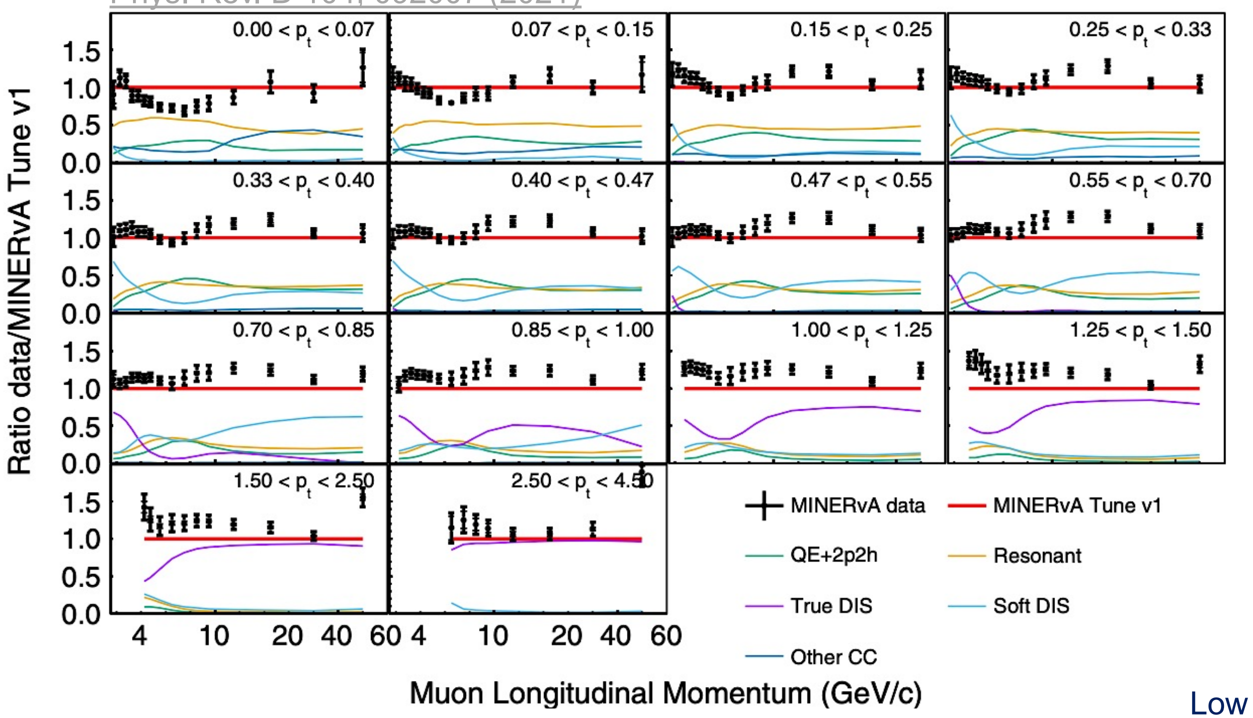
Will we understand SIS transition and DIS interactions sufficiently well in time for DUNE? (And for MO and ν_τ uncertainties for atmospherics)

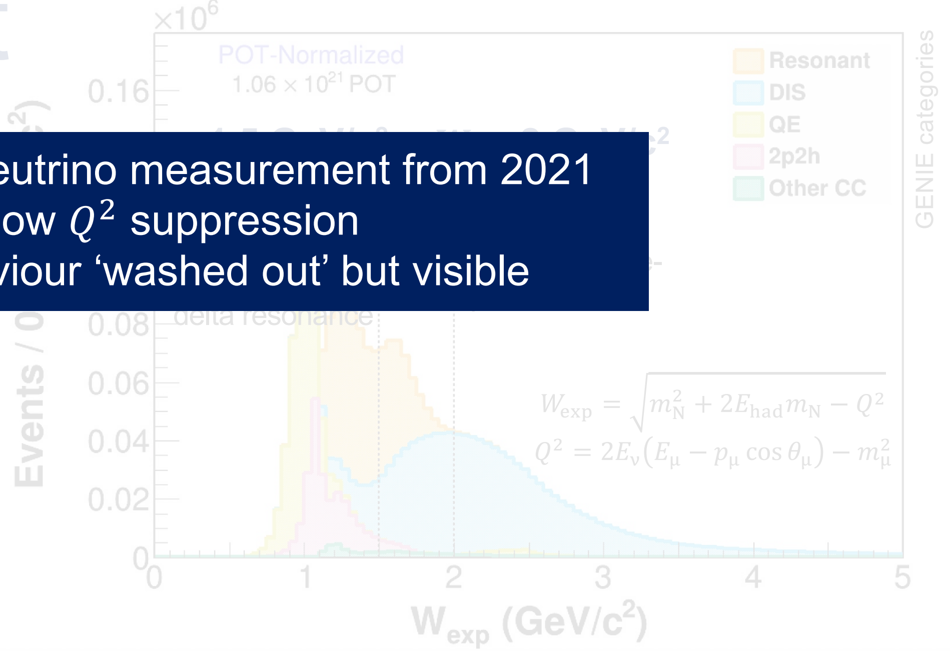
These measurements can indicate where we are missing degrees of freedom (or what) in our models

Will we understand nuclear effects in Ar nucleus in time?

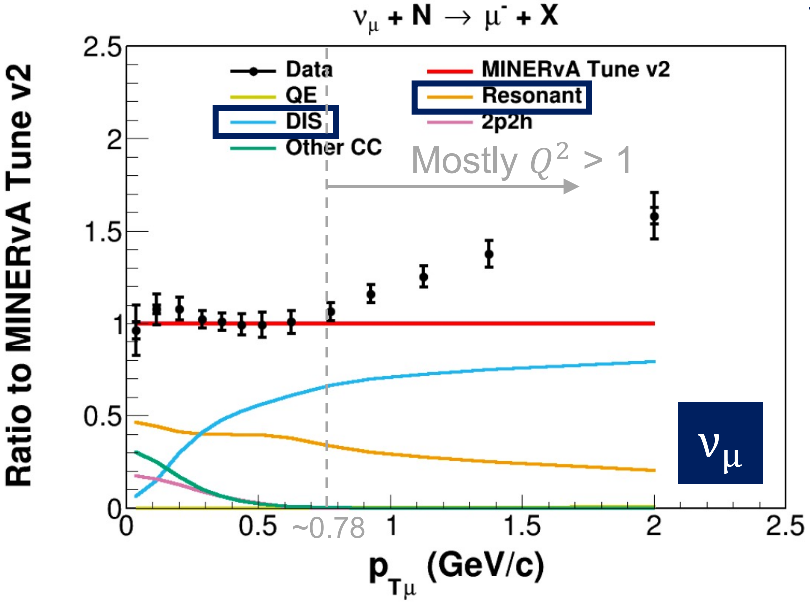
Measurements vs *A* in this region from MINERvA, 2x2 measurements on argon, ND-GAr?

Back-up

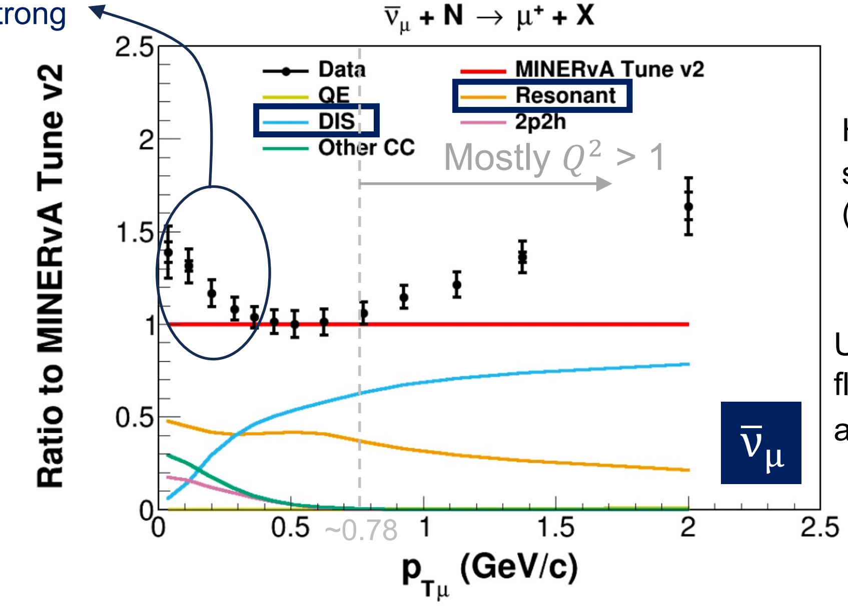




2D inclusive neutrino measurement from 2021
Model had no low Q^2 suppression
High $p_{T\mu}$ behaviour 'washed out' but visible



Low Q^2 suppression too strong



High $p_{T\mu}$ underprediction, shape not quite right (true SIS region with $Q^2 > 1$)

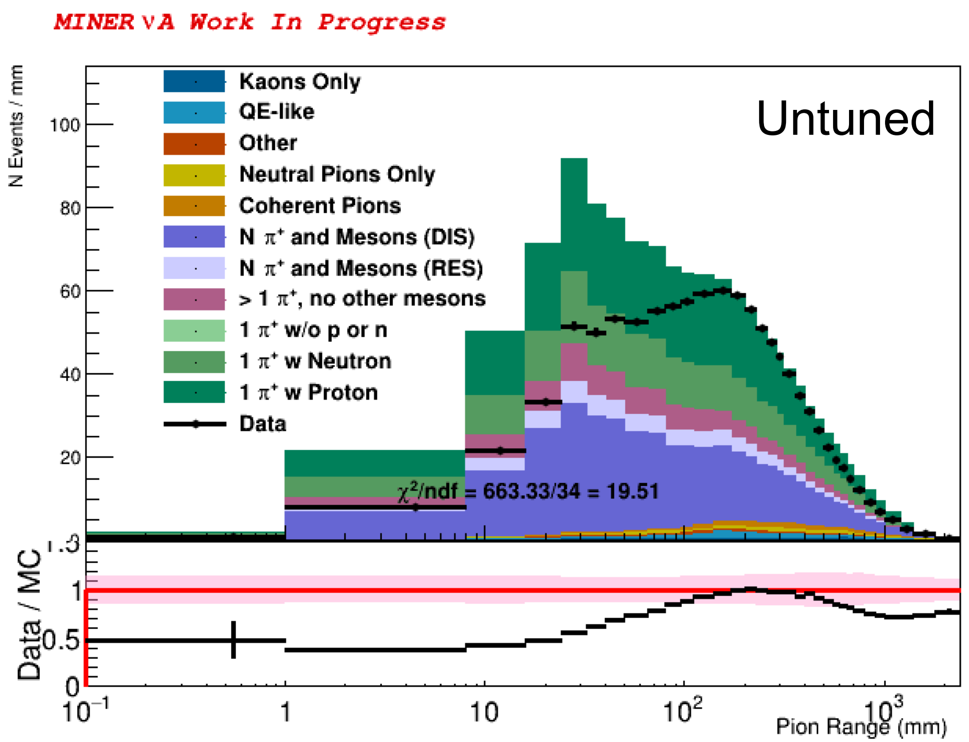
Uncertainties dominated by flux, interaction model ($M_{A/V}^{RES}$), and detector response

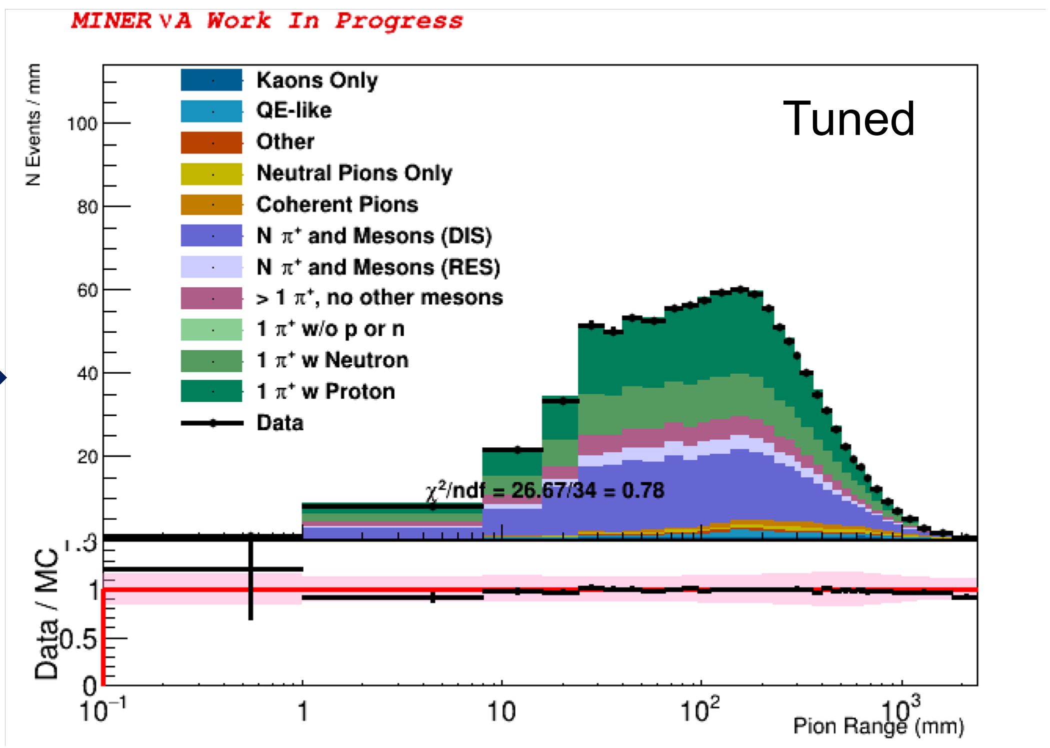
$$Q^2 \approx p_T^2 \left(1 + \mathcal{O}\left(\frac{E_{recoil}}{E_\mu}\right)\right)$$

ME datasets
2 GeV < E_μ < 20 GeV

MINERvA's CC $\nu_\mu \geq 1\pi^+$

- Model unconstrained in this kinematic region (trackless pions down to zero π momenta)
- Tuned to get the smearing right (SVD to study migration between pion range and kinetic energy)

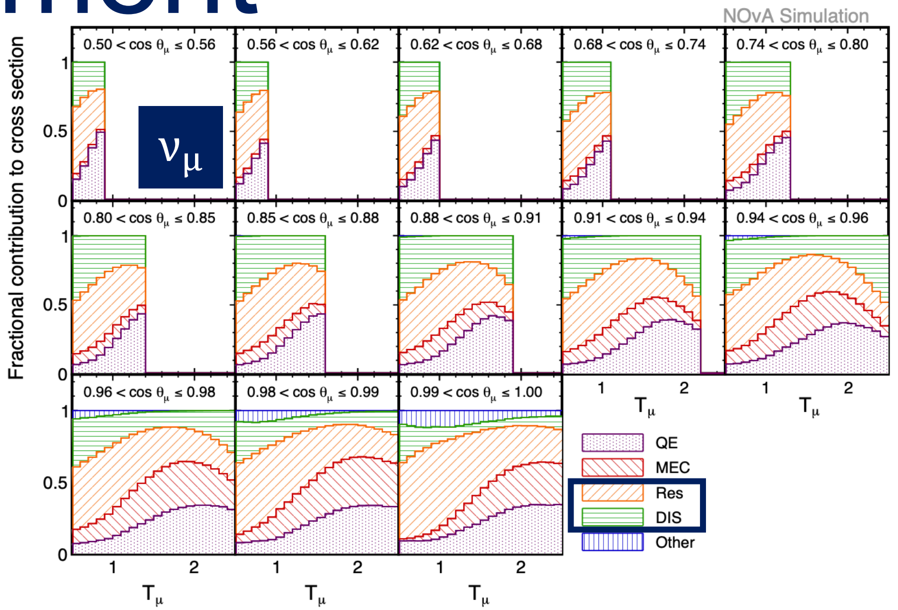




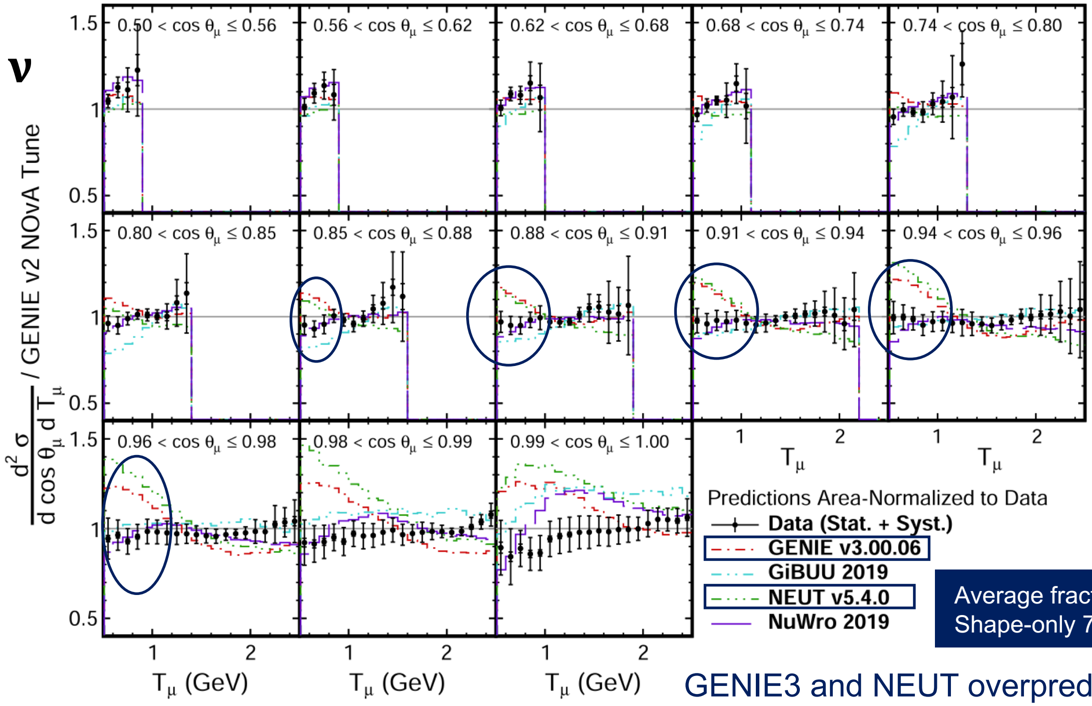
Phys. Rev. D 107, 052011, 2023
P. Singh, Wine&Cheese, 2024

NOvA's inclusive measurement

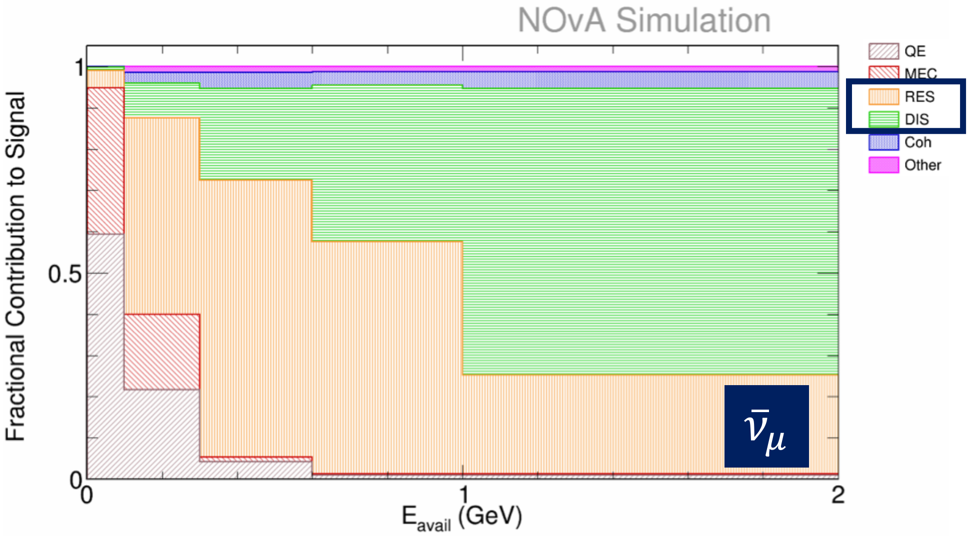
- Slices of T_μ and $\cos\theta_\mu$ in neutrino mode (2023), and T_μ, $\cos\theta_\mu$, E_{avail} (2024)
  - Highly customised GENIE2 (ν) and GENIE3 model ($\bar{\nu}$)
  - Lower T_μ and higher E_{avail} means more Nπ



2D ν



Average fractional uncertainty 12%
Shape-only 7%



GENIE3 and NEUT overprediction at low T_μ and higher $\cos\theta_\mu$

NOvA’s CC $\bar{\nu}$ inclusive

Phys. Rev. D 107, 052011, 2023
P. Singh, Wine&Cheese, 2024

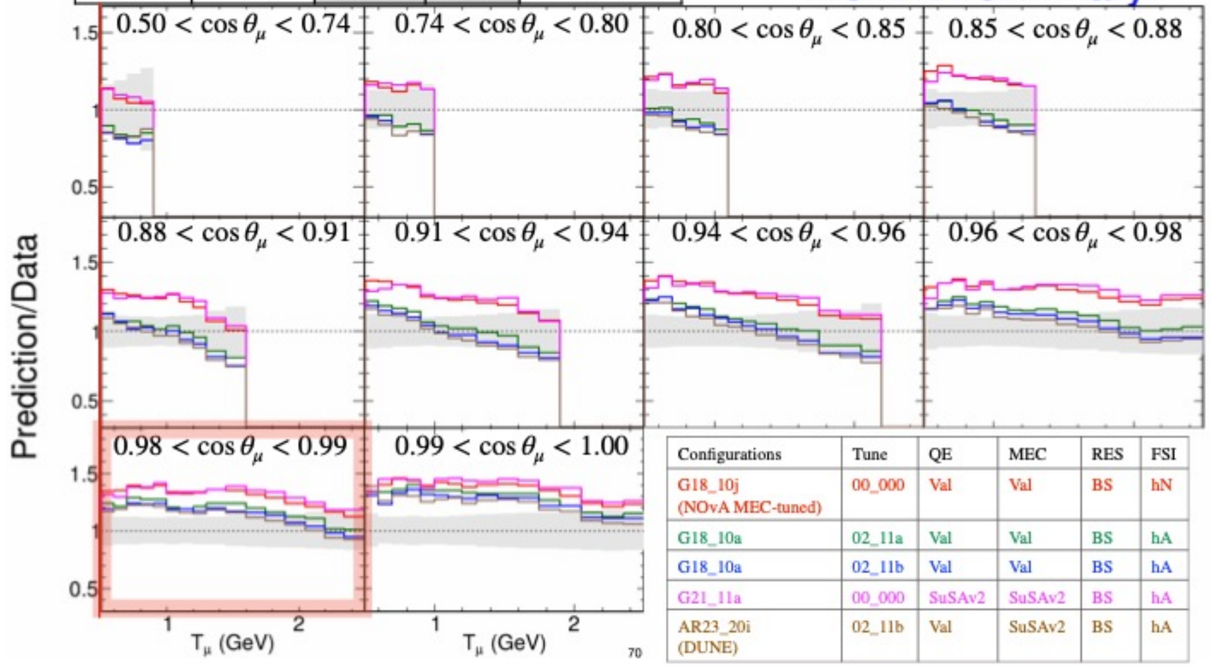
RES dominated, transition

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%



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

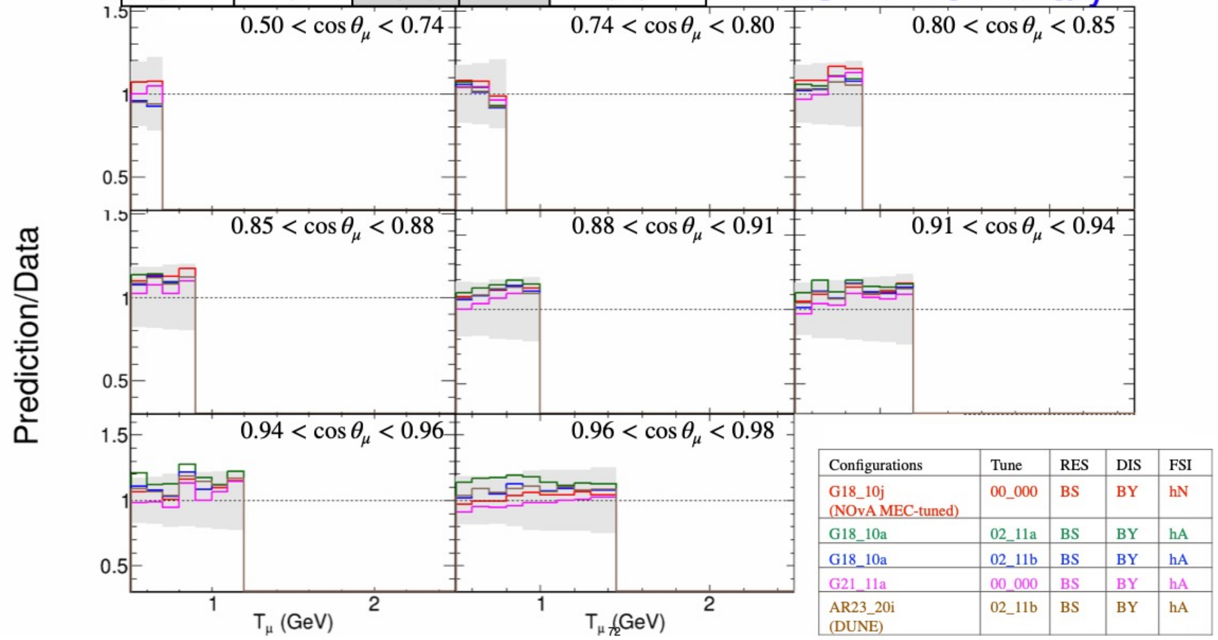
DIS dominated

1 GeV < E_{avail} < 2 GeV

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
0.1	0	23.9	72.2	3.8

Events: 5%



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

Average fractional uncertainty 14%

Similar to neutrinos, GENIE3 overpredicts at lower T_μ and higher $\cos\theta_\mu$

E_{avail} gives power to localise this to mostly RES→DIS transition, less so in DIS

Phys. Rev. D 107, 052011, 2023
P. Singh, Wine&Cheese, 2024

NOvA's CC $\bar{\nu}$ inclusive

RES dominated, transition

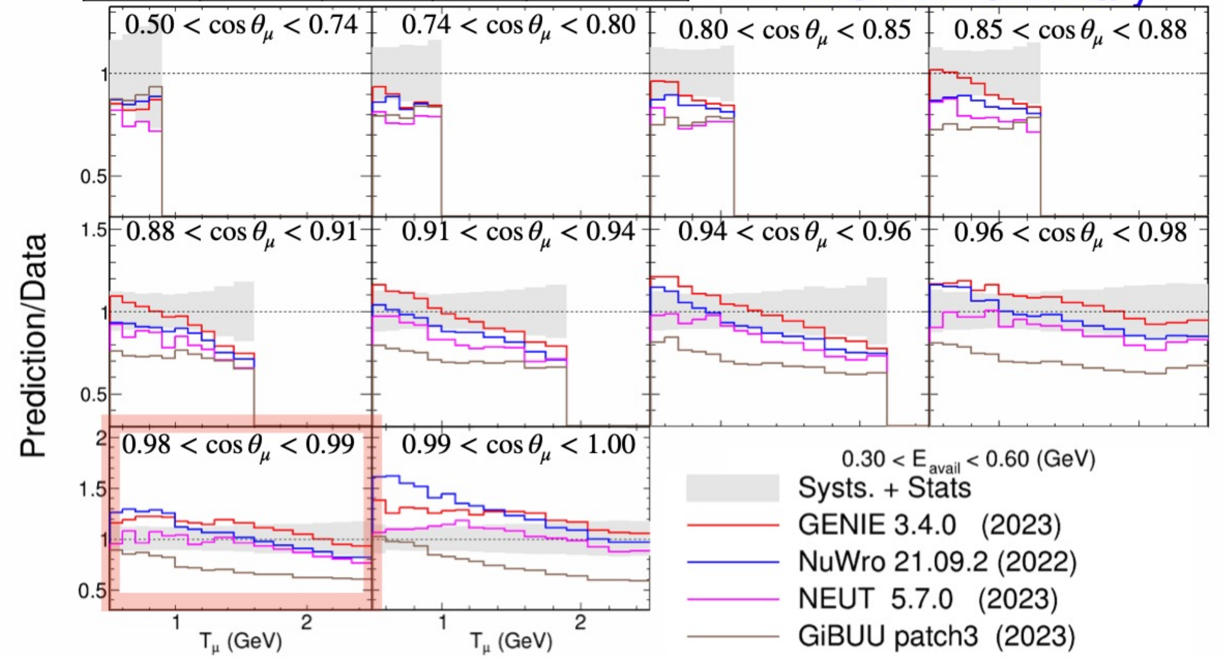
300 MeV < E_{avail} < 600 MeV

Table from NOvA-tuned GENIE

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

Events: 14%

NOvA Preliminary



DIS dominated

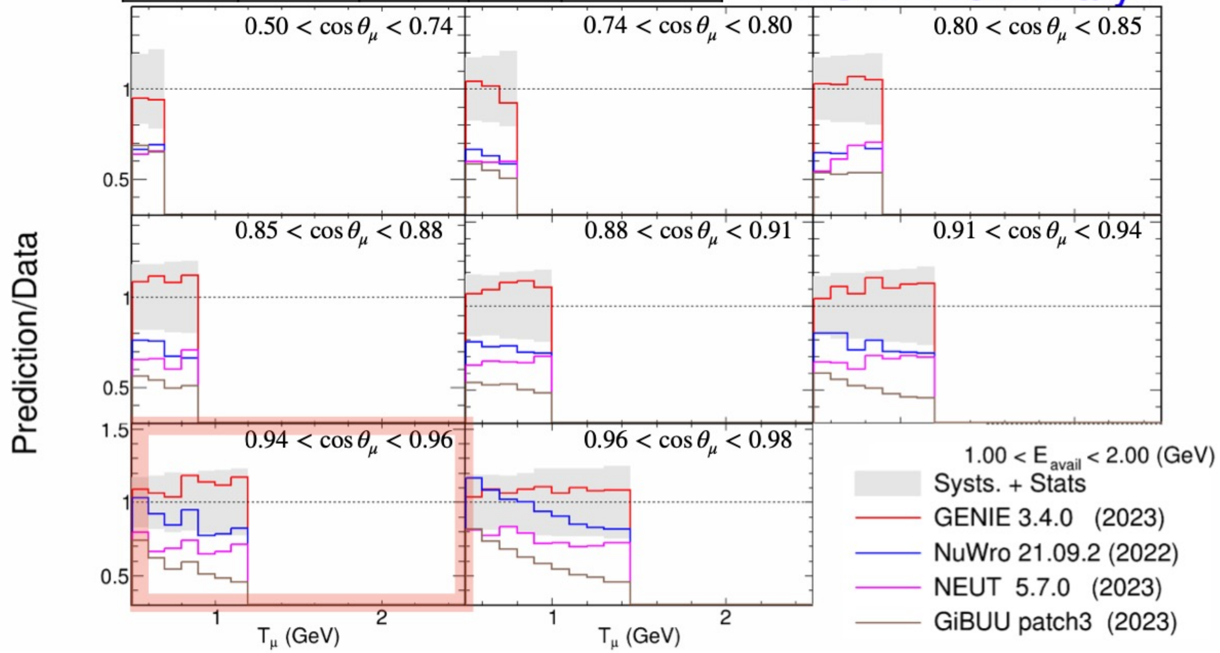
1 GeV < E_{avail} < 2 GeV

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
0.1	0	23.9	72.2	3.8

Events: 5%

NOvA Preliminary



Average fractional uncertainty 14%

Lot of variation in the RES region, NEUT close at lower T_μ and higher $\cos\theta_\mu$
DIS: different FSI with.Bodek-Yang model (except GIBUU) – GENIE seems to model DIS the best

Models

- **NOvA 2D:** GENIE 2.12.2 (RFG with high-momentum tail, QE Llewellyn-Smith, empirical 2p2h, Rein-Sehgal RES, DIS Bodek-Yang, custom hadronization Pythia 6, FSI hA) + QE MA =1.04 GeV/c^2 based on ANL/BNL, 57% reduction of single pion non-resonant production, neutrino and antineutrino weights from neutrino NOvA ND fit to empirical MEC (Eur. J. Phys. C 80, 1119 (2020))
- **NOvA 3D:** GENIE 3.0.6 (LFG, QE Valencia+Z-expansion, Valencia MEC and RPA, Berger-Sehgal RES, DIS Bodek-Yang, custom hadronization Pythia 6, FSI hN) + FSI and MEC tuned
- **NEUT 5.4.0:** LFG, QE Valencia, MEC Valencia, Rein-Sehgal RES, DIS Bodek-Yang, Pythia 5, FSI Oset+external data
- **NEUT 5.7.0:** LFG, QE Valencia, MEC Valencia, RES Rein Sehgal, DIS Bodek-Yang, FSI Oset+external data
- **GENIE 3.4.0 (DUNE):** spectral function LFG, QE Valencia, SuSAv2 MEC, Berger-Sehgal RES, DIS Bodek-Yang, custom hadronization Pythia 6, FSI hA

MINERvA model

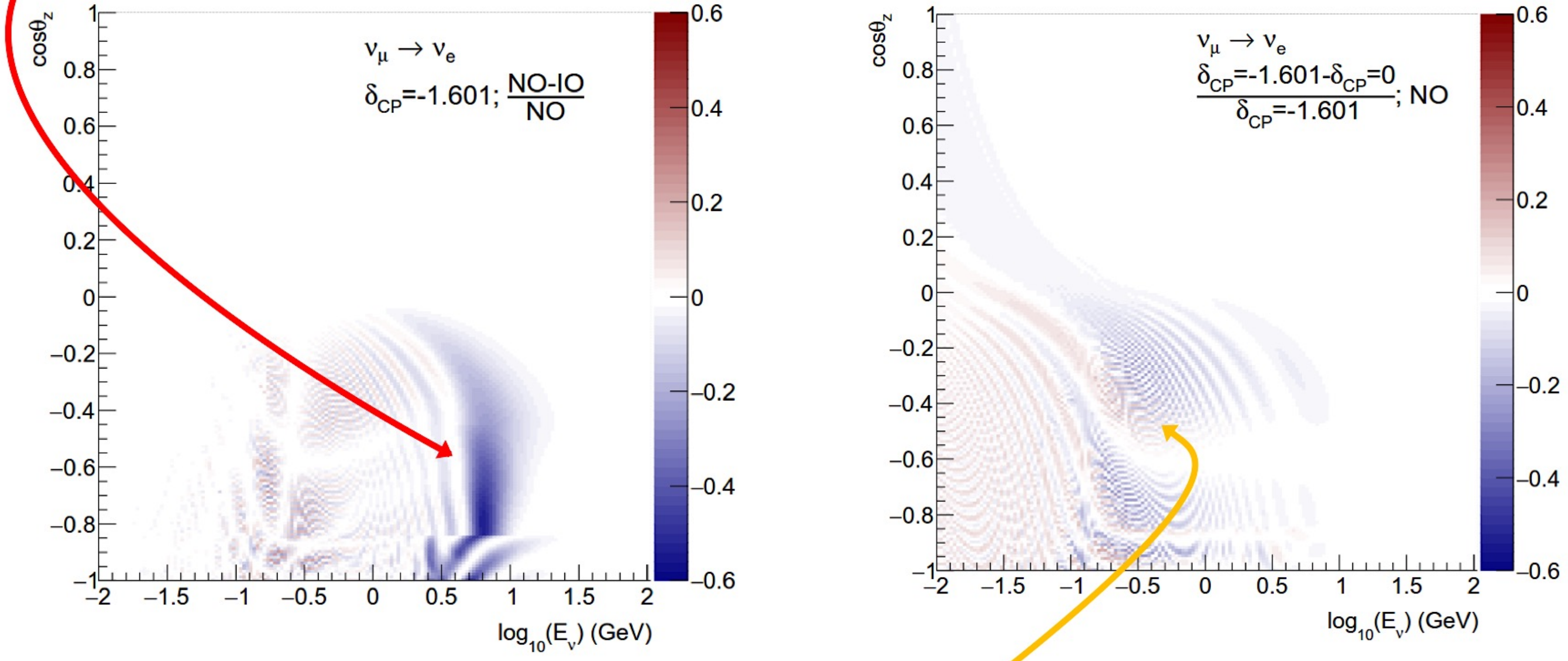
- GENIE 2.12.6
  - QE – Llewellyn-Smith formalism with the vector form factors modeled using the BBBA05 model
  - RES – Rein-Sehgal model
  - DIS – a leading order model with the Bodek-Yang prescription
  - Nuclear environment – relativistic Fermi gas with additional Bodek-Ritchie high momentum tail
  - FSI – INTRANUKE-hA
- MINERvA modifications based on our data
  - Added RPA to better simulate QE
  - Added + enhanced Valencia 2p2h – increased by 50% over the nominal prediction (integrated over all phase space) based on low recoil fit
  - Non-resonant pion production reduced to 43%
  - FSI reweight
- V2: Low Q^2 suppression
- V4.3.1: Coherent Pion Reweight, Diffractive Reweight, Low Q^2 Pion Reweight based on ME $CC1\pi^+$

Models

Generators	Initial State Interactions	QE	MEC	RES/Coh	DIS	FSI
GENIE 3.4.0 (2023) (DUNE) AR23_20i_02_11b	Spectral function, LFG	Valencia	SuSAv2	BS	BY	hA
NuWro 21.09.02 (2022)	LFG	Llewellyn-Smith (LS)	Valencia	NuWro RES model	BY	NuWro FSI model
NEUT 5.7.0 (2023)	LFG	Valencia	Valencia	BS/RS	BY	Custom semi-classical intranuclear cascade (INC) model
GiBUU patch3 (2023)	Modified LFG	Dipole Form Factor, RPA corrections	Semi-inclusive electron scattering data	MAID (electromagnetic form factors)	BY	BUU transport model

Atmospheric neutrinos

- Atmospheric neutrinos have sensitivity to mass ordering via 3-10 GeV resonance
  - Opposite effect for neutrino and anti-neutrinos: **need to separate**
  - Contribution from $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$, where ν_τ enters multi-ring ν_e sample



- δ_{CP} sensitivity from ν_e below 1 GeV → ν_e/ν_μ important
- **Neutrino flavour differences** also limiting atmospheric results

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