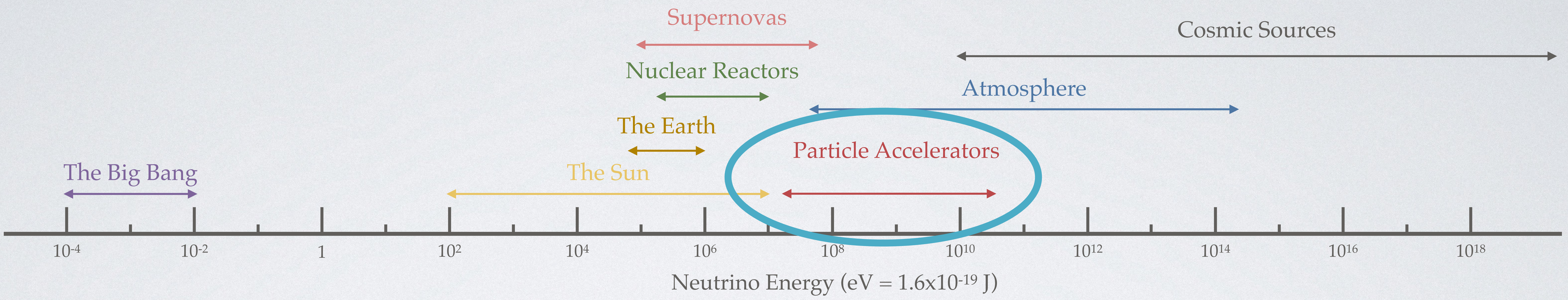
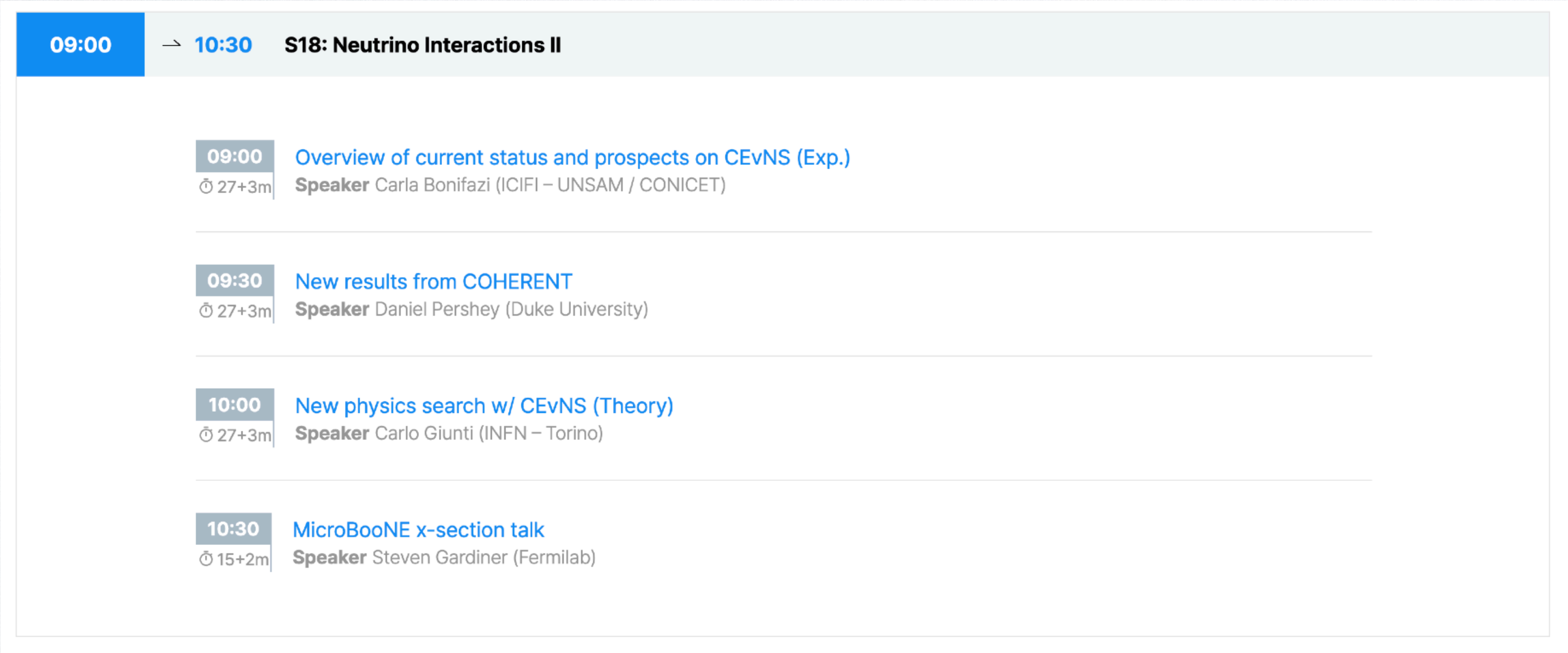
RECENT NEUTRINO CROSS SECTION MEASUREMENTS

Laura Fields, University of Notre Dame
Neutrino 2022

SCOPE

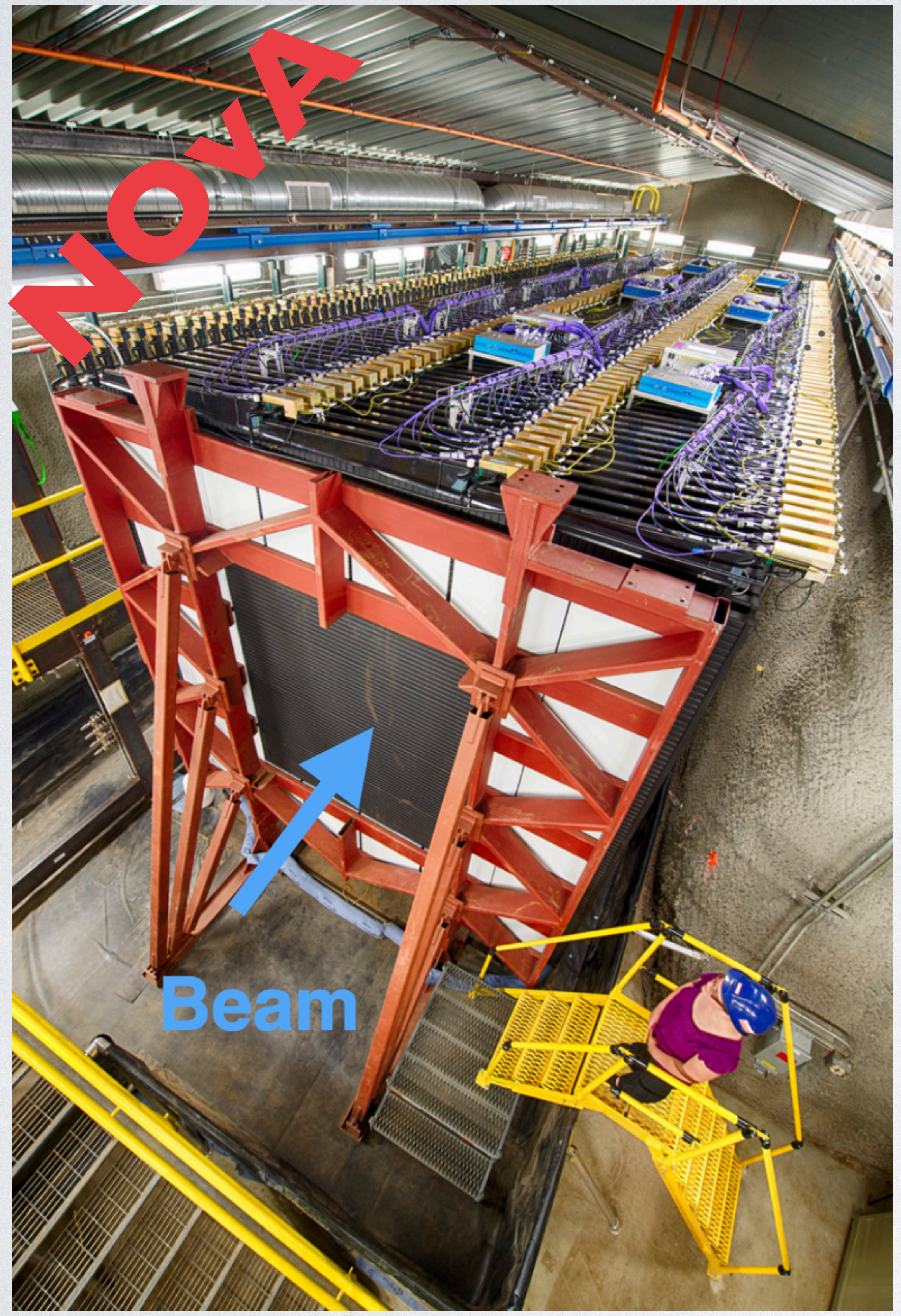


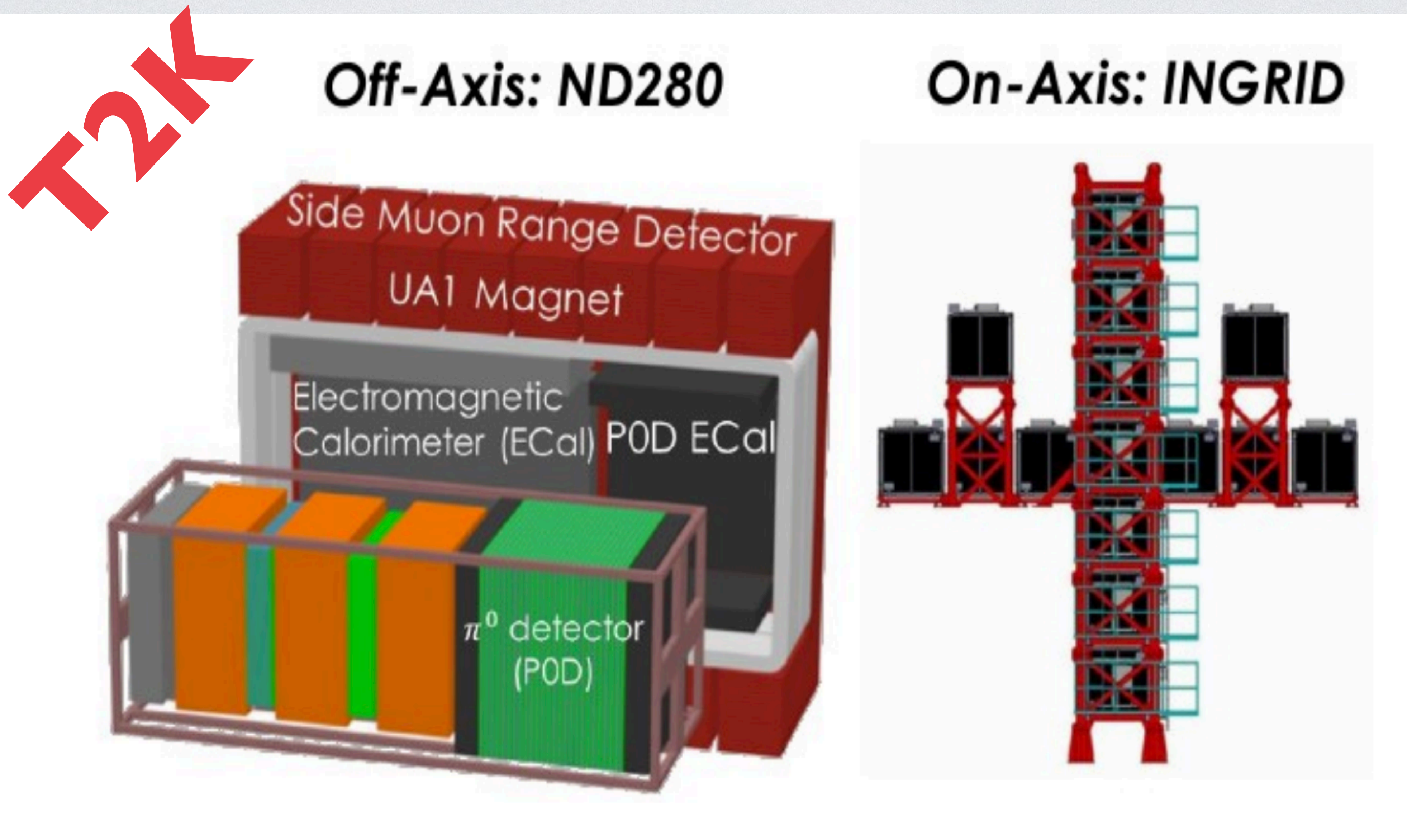
I'm going to focus on on the recent cross-section measurements using conventional accelerator-based neutrino beams



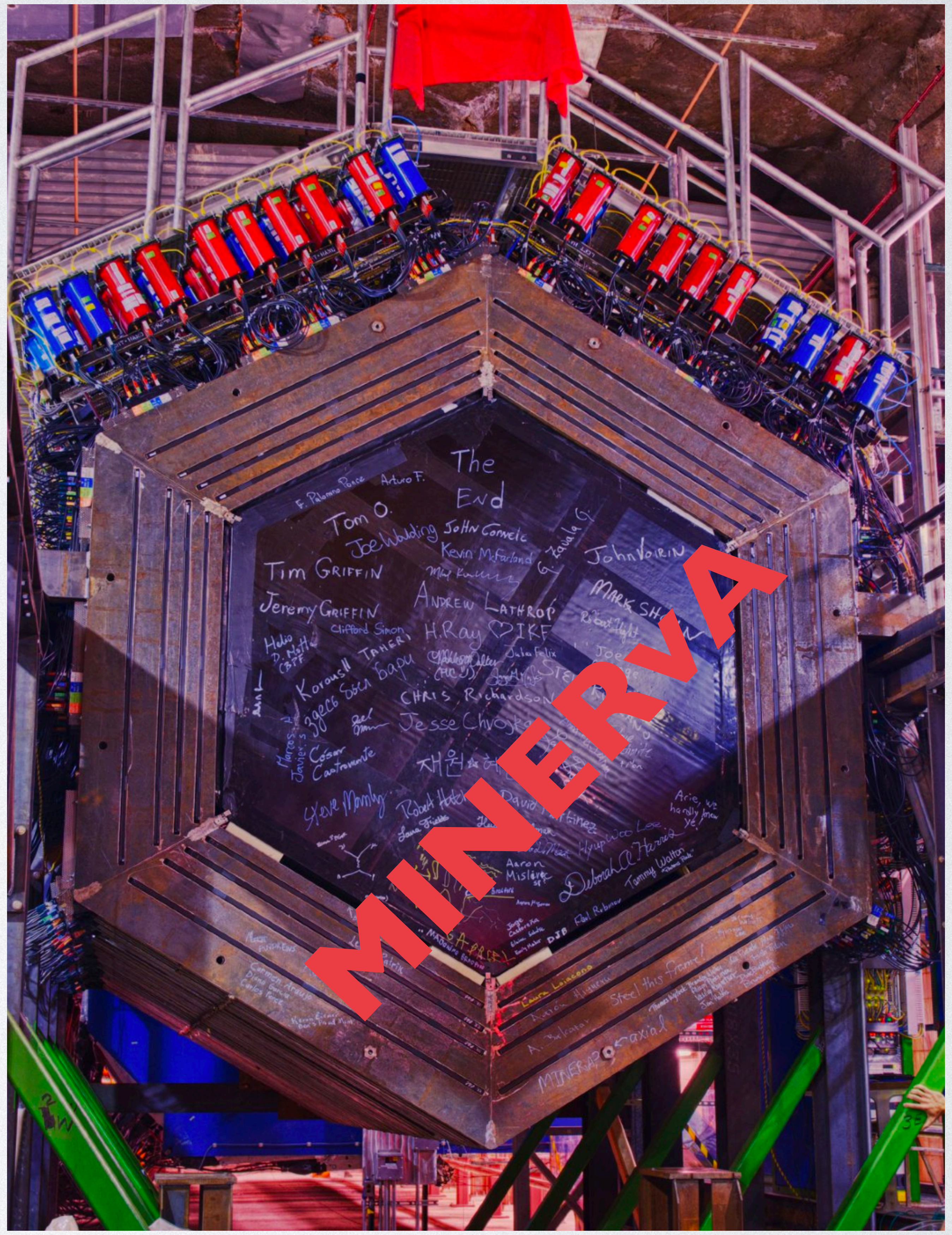
- But stay tuned to the next session (tomorrow morning Korean time) for news on low energy cross sections!

SCOPE


NOvA
Beam


T2K
Off-Axis: ND280
On-Axis: INGRID
Side Muon Range Detector
UA1 Magnet
Electromagnetic Calorimeter (ECal)
P0D ECal
π^0 detector (P0D)


MicroBooNE


MINERvA

SCOPE

193 tons
PVC cells + **liquid scintillator**
$\bar{E}_\nu$ ~ 1.8 GeV

On Axis
0.6 tons **H_20**
0.3 ton plastic **scintillator**
100 ton **Fe**
$\bar{E}_\nu$ ~ 0.86 GeV

Off Axis
1.5 tons **Plastic Scintillator**
0.5 tons **Water**
3 tons **Water** (PØD)
$\bar{E}_\nu$ ~ 0.6 GeV

85 tons **Argon**
$\bar{E}_\nu$ ~ 0.8 GeV (BnB)
$\bar{E}_\nu$ ~ 0.9 GeV (NuMI)

0.2 tons **Carbon**
0.6 tons **Iron**
0.7 tons **Lead**
0.4 tons **Water**
0.2 tons Helium
5.5 tons **Plastic Scintillator**

E ~ 3 GeV (Low Energy)
E ~ 6 GeV (Med Energy)

MOTIVATION

- Cross sections are **critical inputs to oscillation** measurements

Event Rate
(ie what we measure)

Oscillation probability —
what we want to know

$$R(\vec{x}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_A \rightarrow \nu_B)$$

Neutrino flux

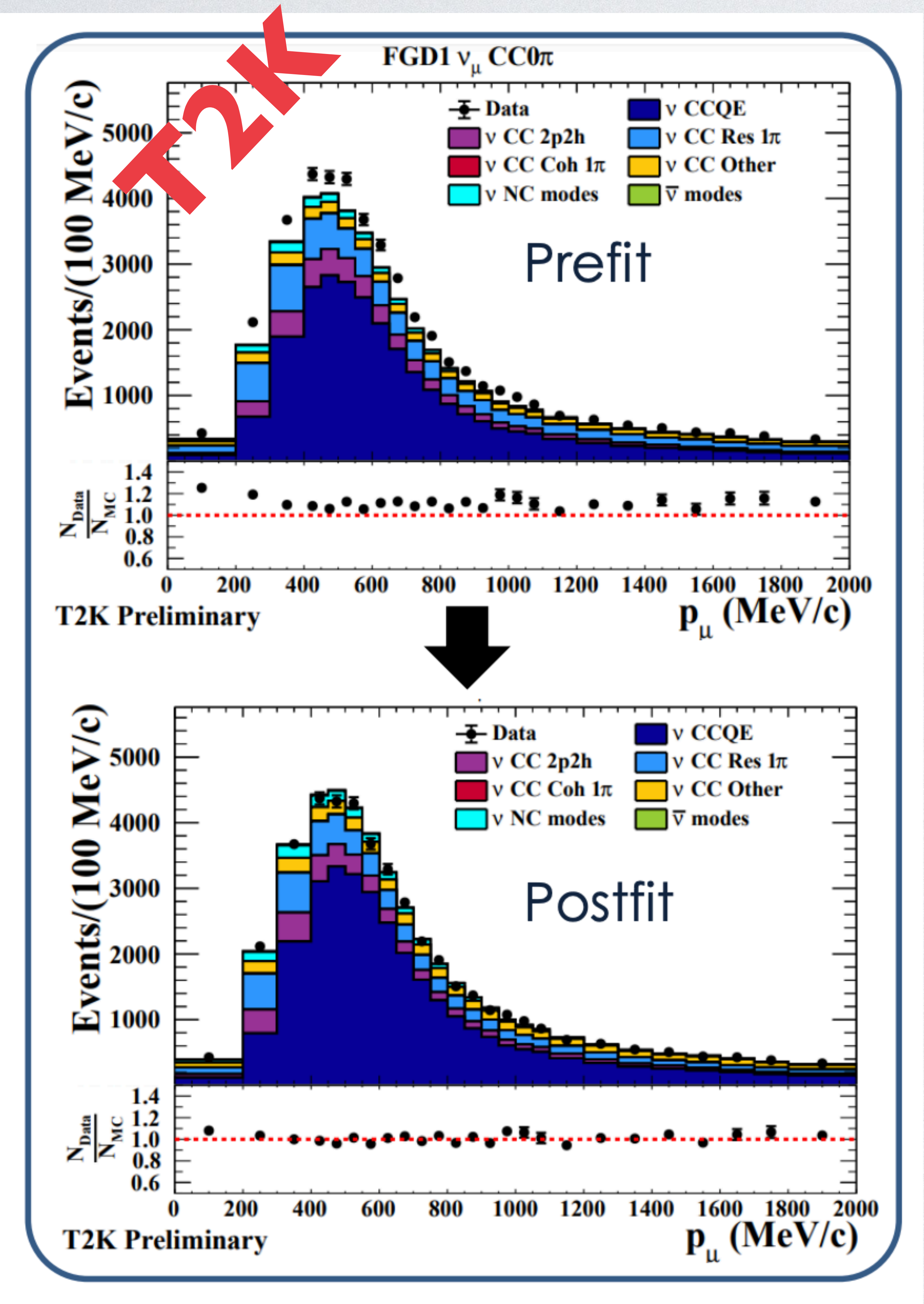
Neutrino interaction cross section

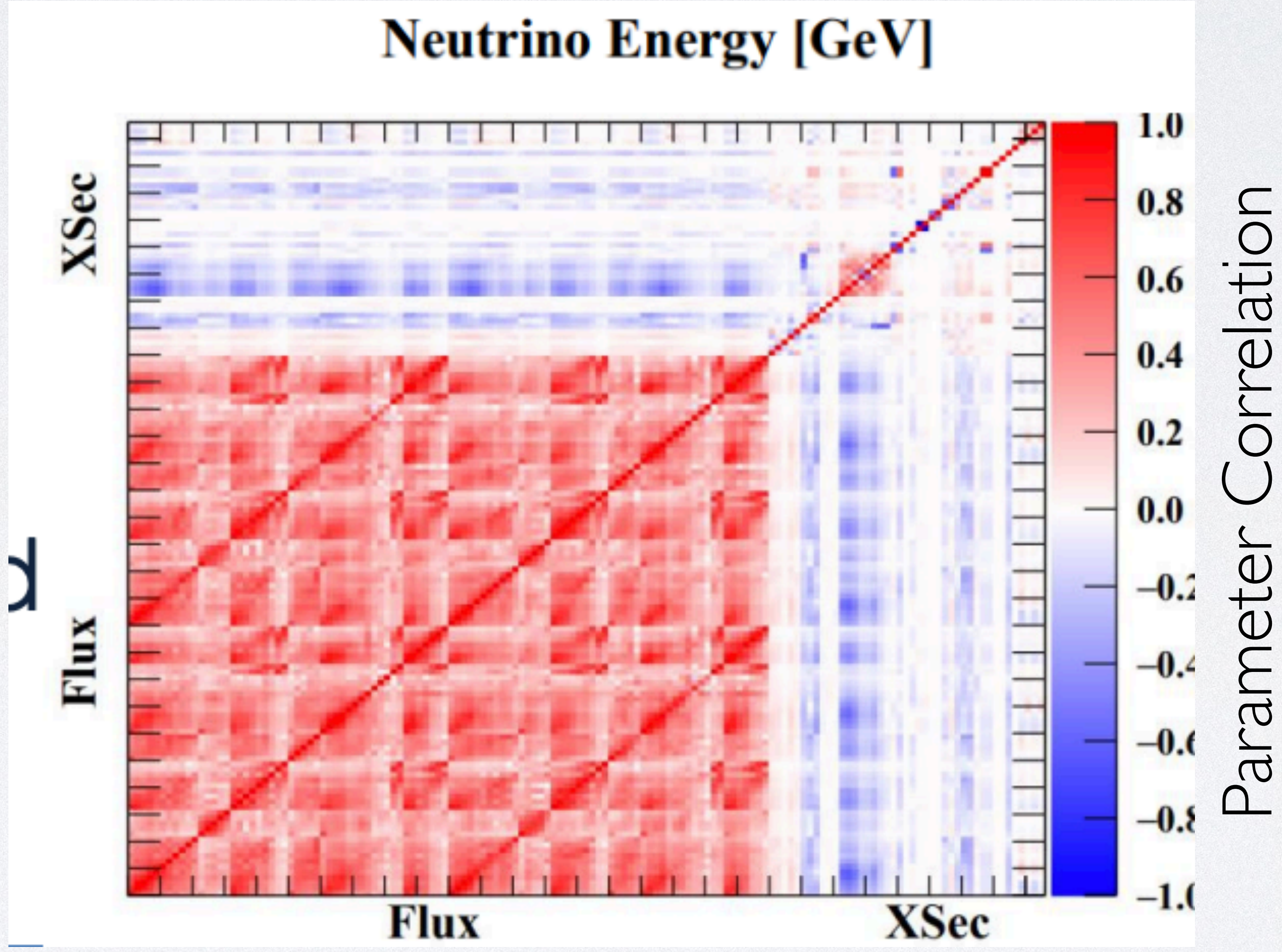
Detector response

To get to oscillation probabilities from event rates, we must know these these well

MOTIVATION

- **Near detectors help**, but they don't start from scratch:

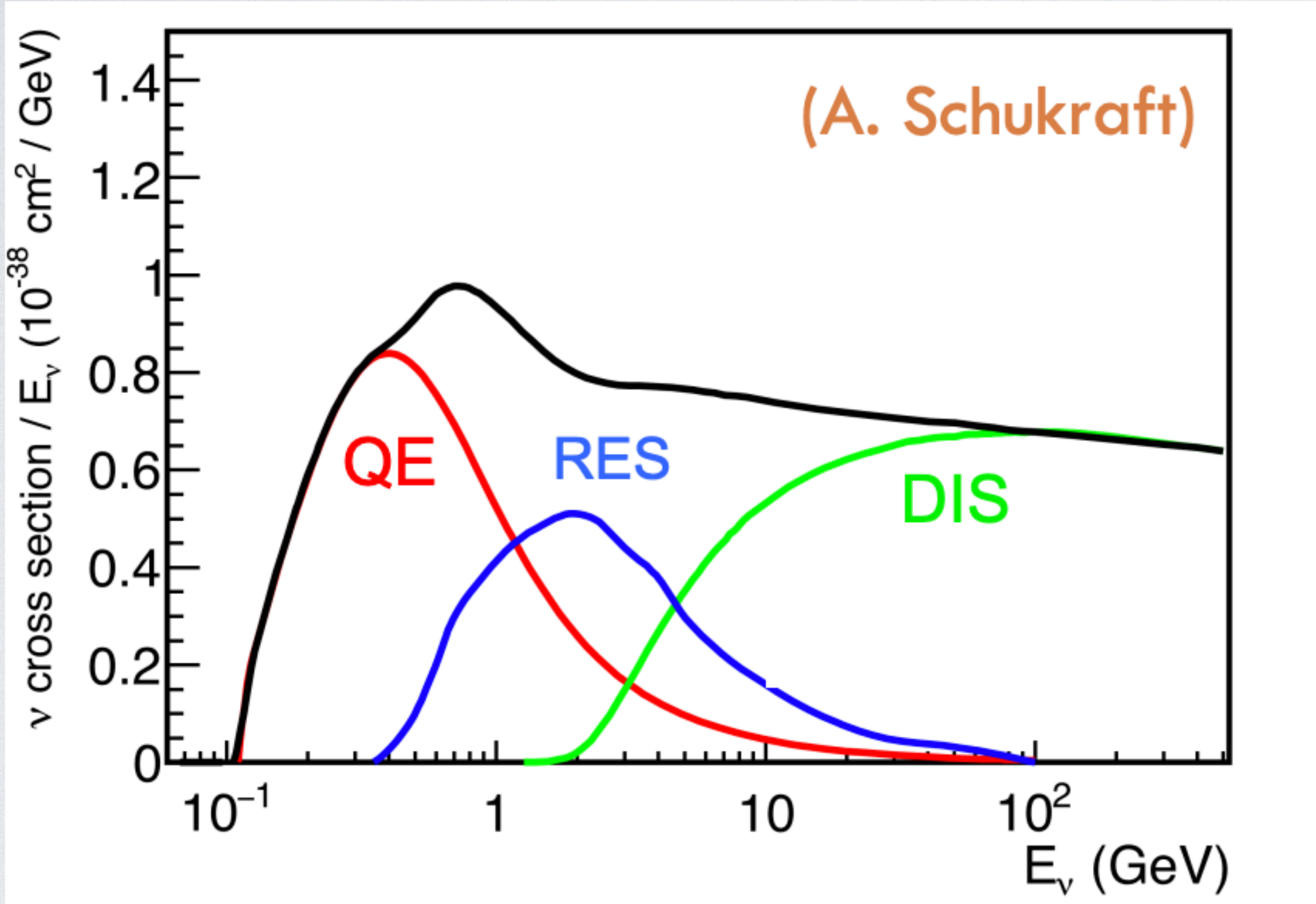


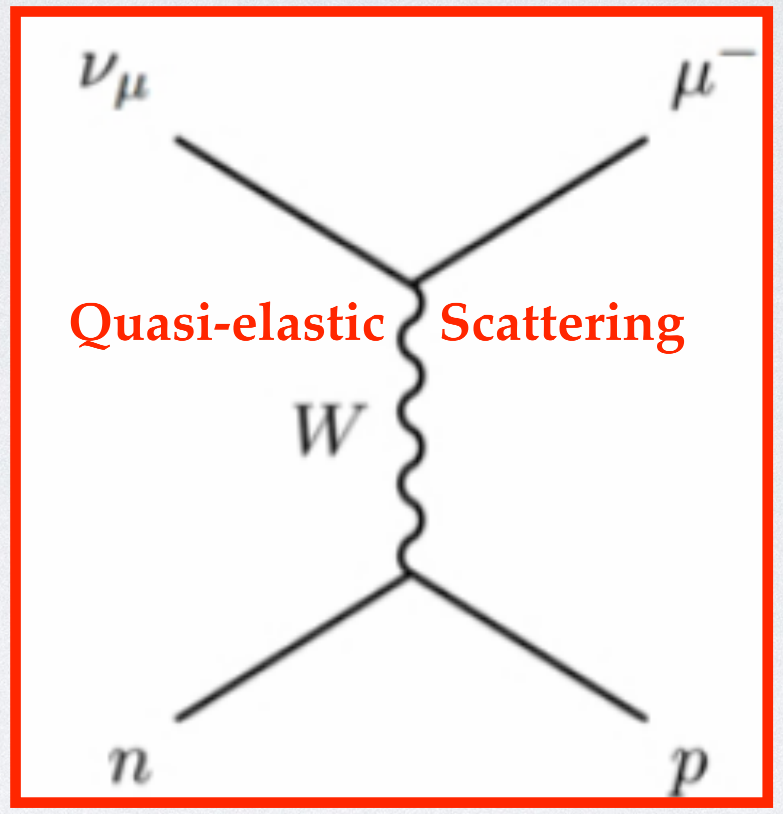


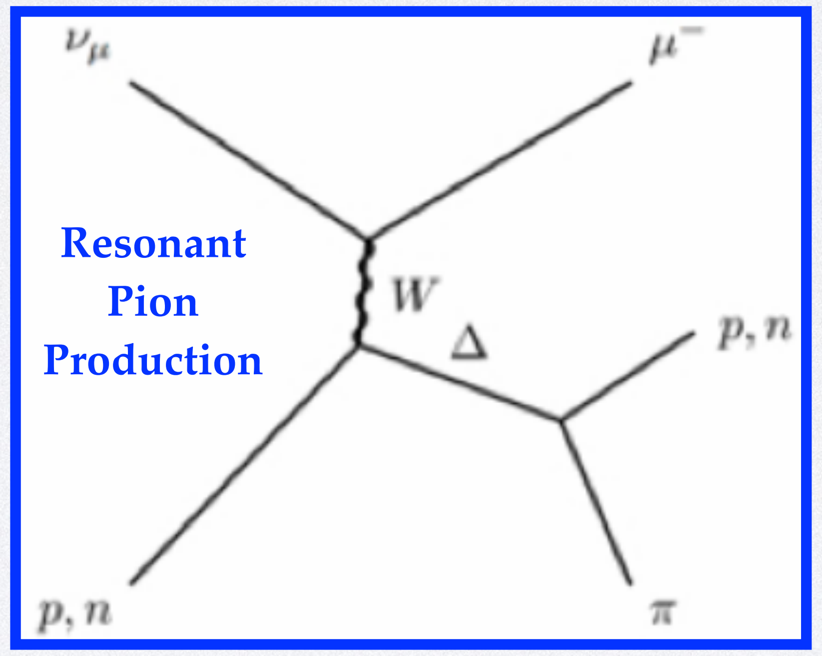
S. Dolan EPS-HEP 2021

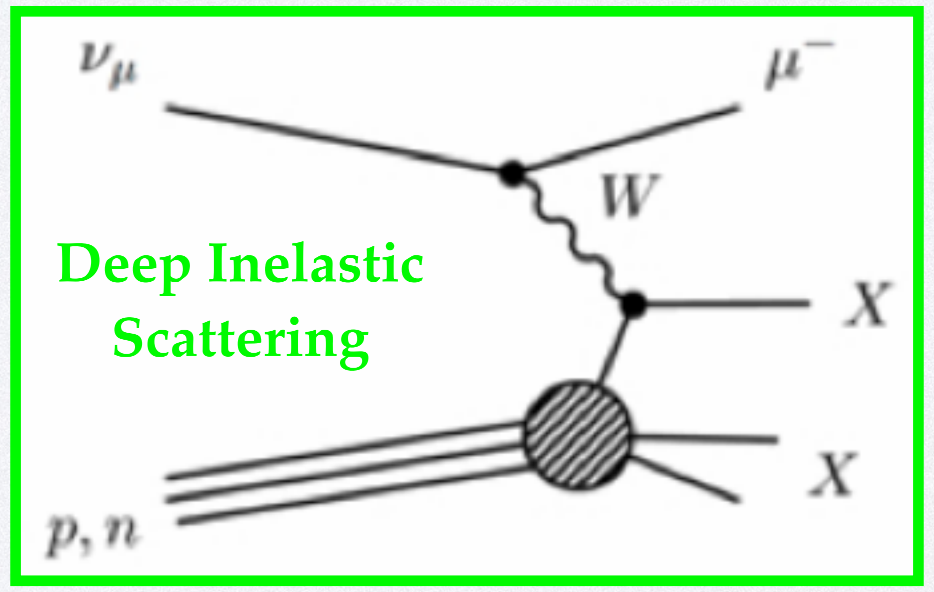
- Oscillation fits using near and far detectors start from **detailed neutrino interaction models**
- And **degrees of freedom** in those models
- **Cross section measurements are input** to these models

WHAT ARE WE MEASURING?



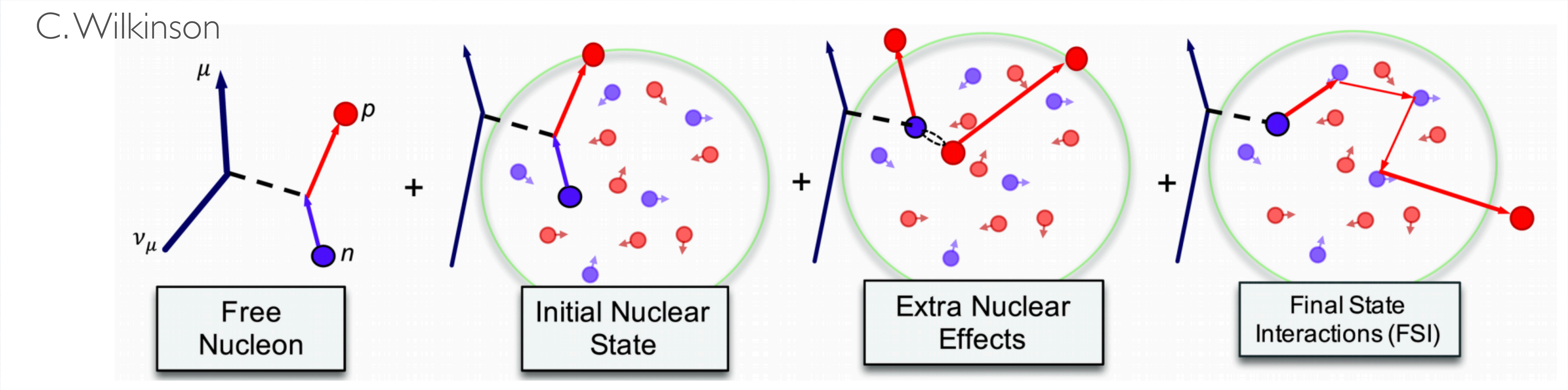






- Most oscillation measurements **focus on charged-current** interactions
  - NC interactions can be backgrounds
- **Three processes dominate** the charged current cross section
- **Lots of other processes** going on:
  - Interactions with multinucleon bound states **(2p2h)**
  - **Coherent** scattering
  - Interactions with **electrons**
  - ???

WHAT ARE WE MEASURING?



- Neutrino-nucleon interactions are also **impacted by many nuclear effects**
- We need models of all of these too, but can **only measure the superposition** of many effects
  - Need **many measurements** to disentangle

THE BASIC FORMULA

Unfolding function that corrects for detector smearing

Number of Events Observed

Estimated number of background events

$$\sigma_i = \frac{U_{ij}(N_j - B_j)}{\Phi_i T \varepsilon_i}$$

Neutrino Flux

Number of Targets

Efficiency

- **Relatively simple formula** for measuring cross sections
- But there **many pitfalls** at each step
- Each **measurement takes many years** to complete

MODELS

- **Cross section measurements require a simulation** (“reference model”) to correct data for backgrounds and detector smearing and acceptance/efficiency
- Corrected cross sections are also typically **compared with many models**
- Models are typically implemented in one of the **four event generators on the market**

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

NEUT

NuWro
Wrocław Neutrino Event Generator

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

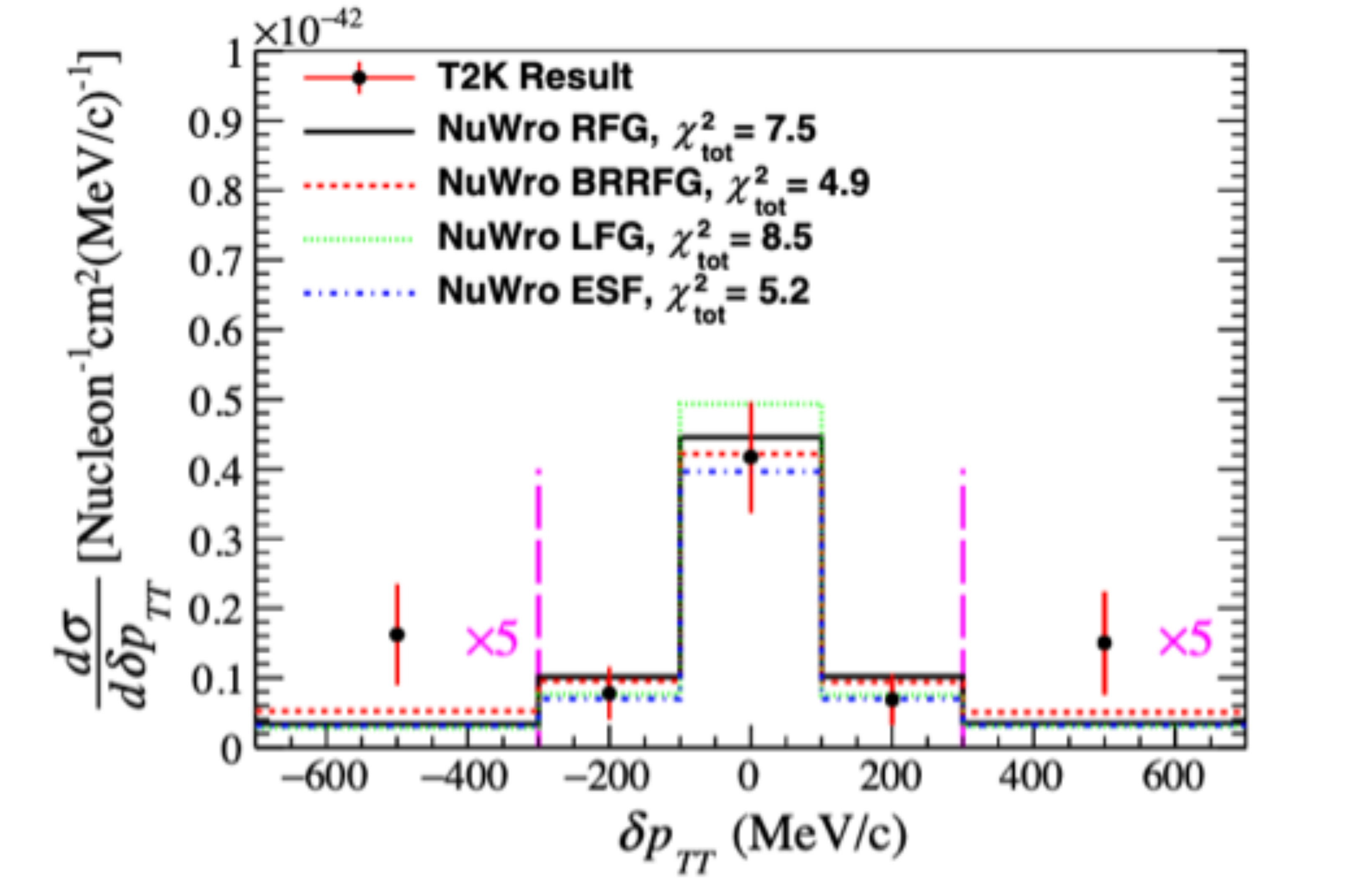
Tuned GENIE used as reference model for MicroBooNE, MINERvA, and NOvA

NEUT used as reference model for T2K

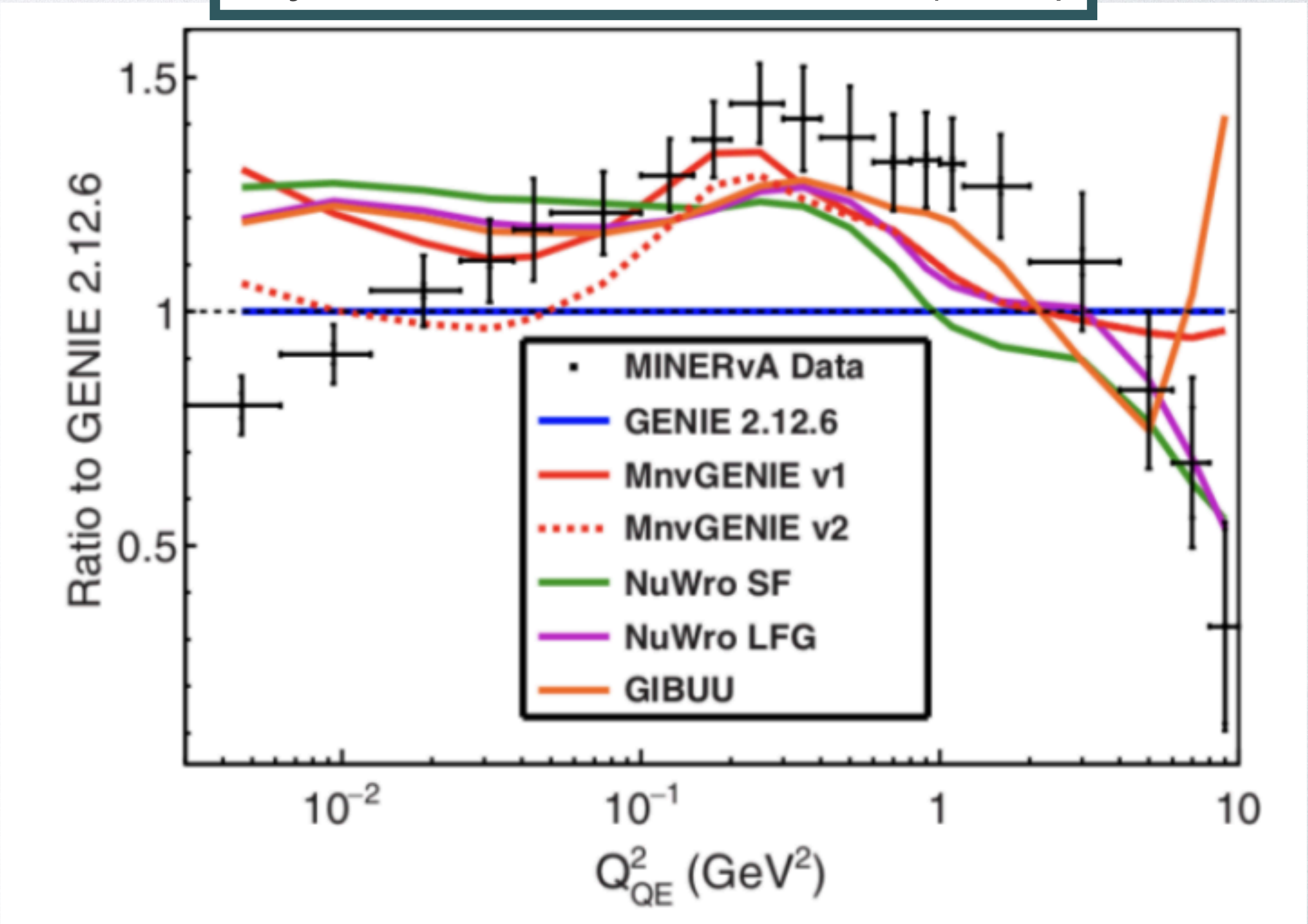
MODELS

- Many generators offer various **model options**
- Some of the models you'll see mentioned in these slides
  - **Initial state nucleon** models
    - RFG: Relativistic Fermi Gas
      - BRRFG: RFG with Bodek-Ritchie high tail added to initial state nucleon momentum distribution
    - LFG: Local Fermi Gas
    - SF: Spectral Function
      - ESF: Effective approximation of a spectral function
  - **2p2h**: Addition of interactions with bound nucleon pairs
  - **SuSA**: Super Scaling Approach
  - **Final State Interaction** Models:
    - hA
    - hN

PHYSICAL REVIEW D 103, 112009 (2021)

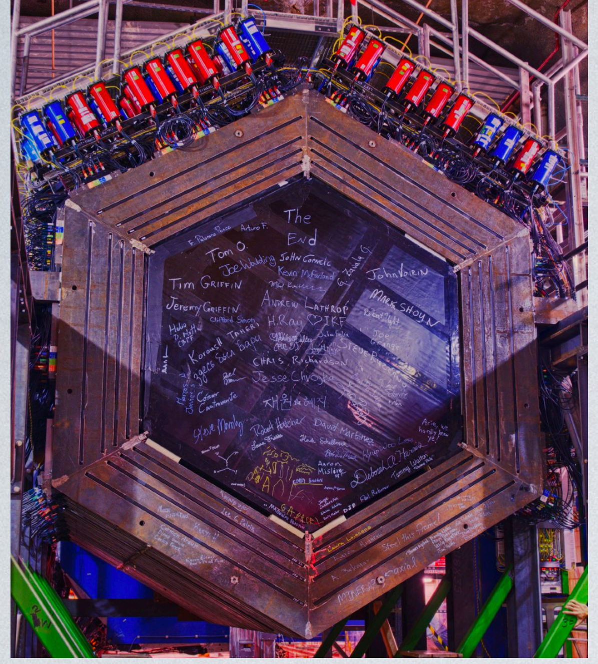


Phys. Rev. Lett. 124, 121801 (2020)



(MOST OF) THE REST OF THIS TALK

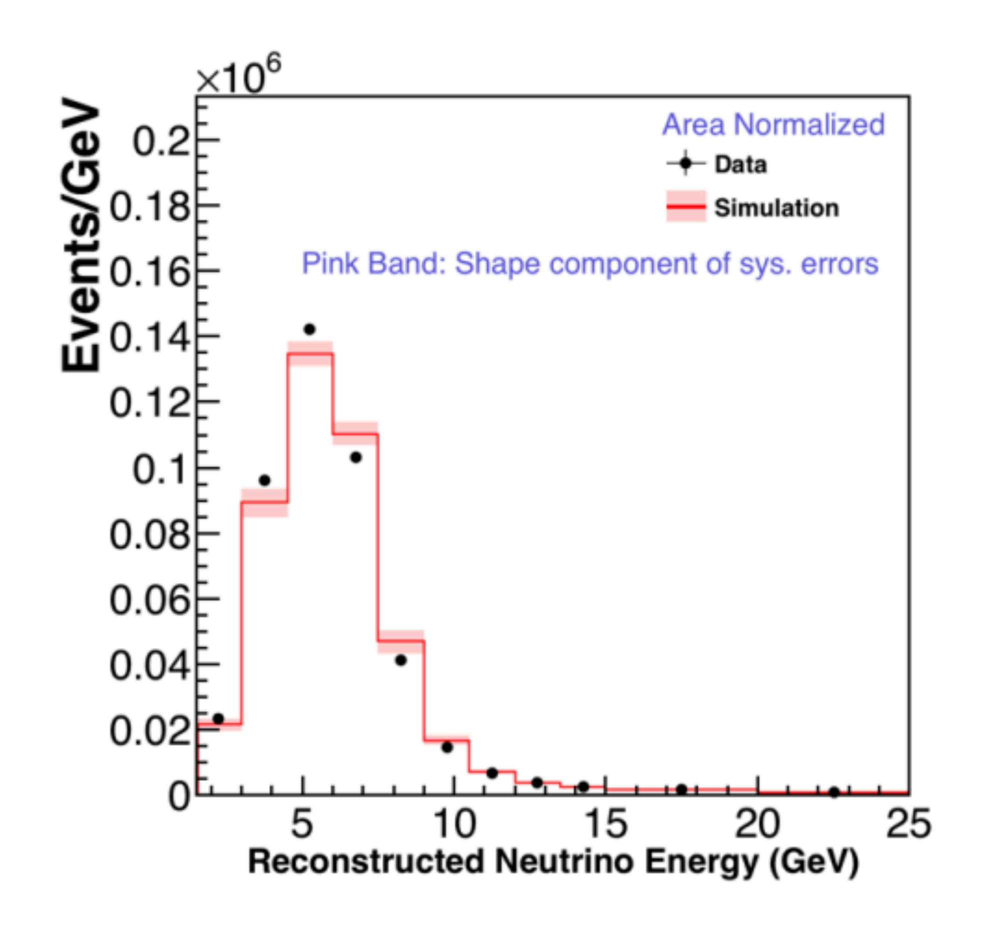
- Recent Cross Section Measurements
  - **Cross Sections to measure neutrino flux**
  - **0 π**
  - **1 π**
  - **Inclusive measurements**

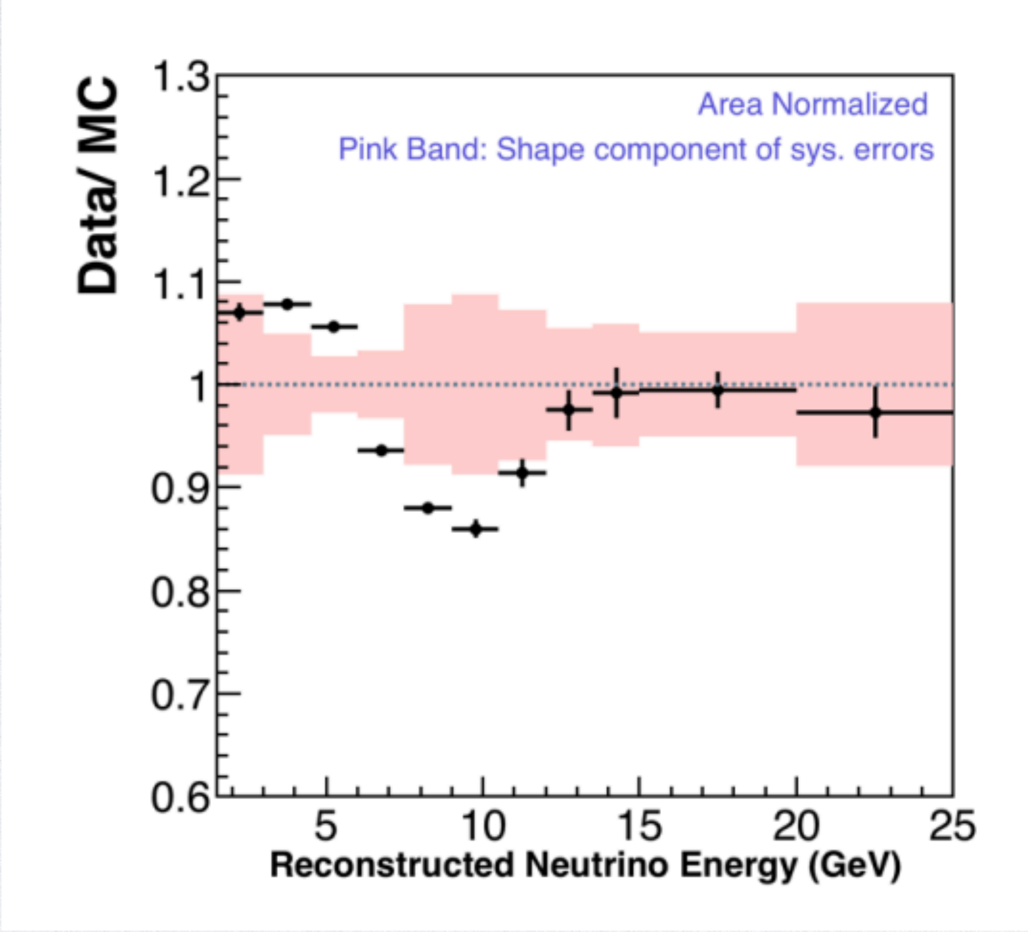


FLUX MEASUREMENTS: MINERVA

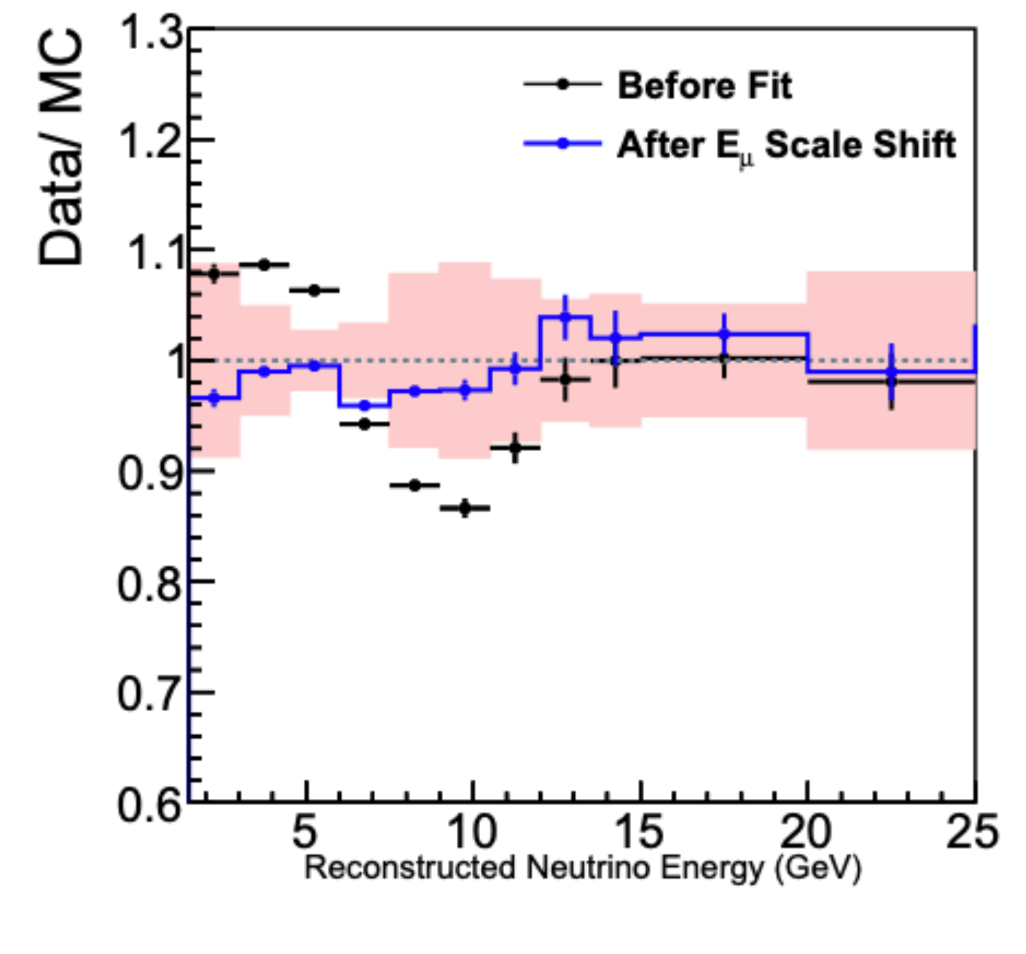
Journal of Instrumentation 16 P08068 (2021)

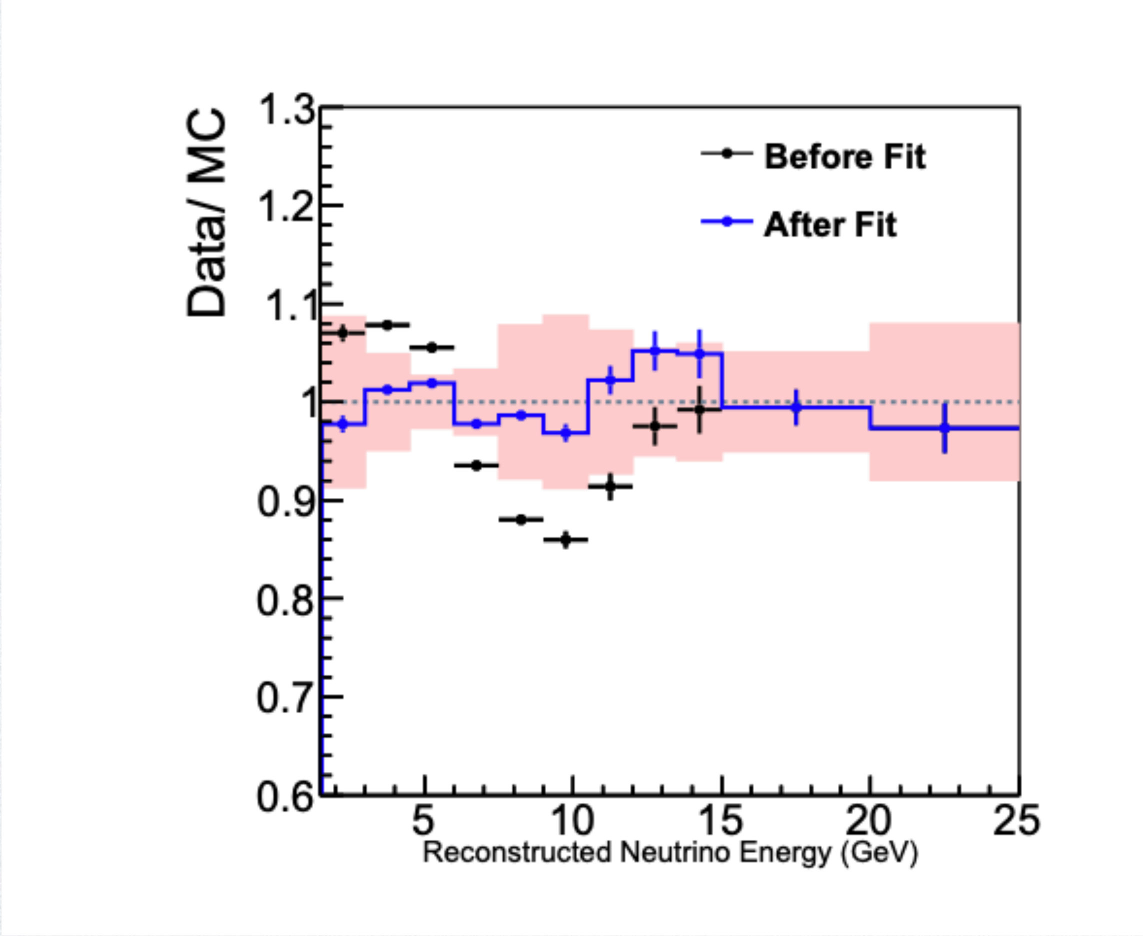
FLUX

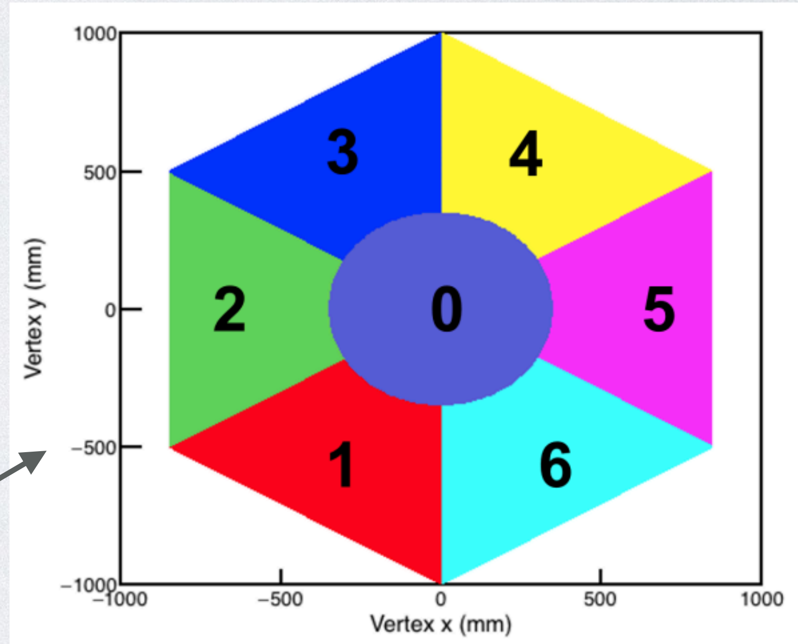


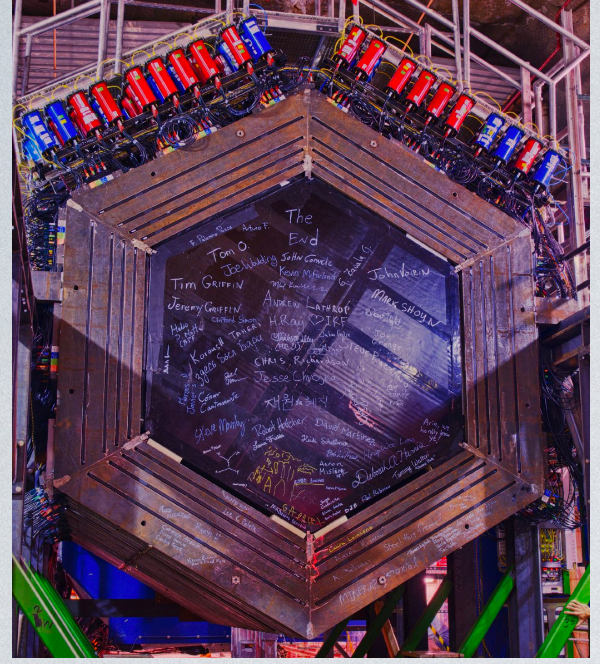


- **Charged-current ν_μ events with low recoil (low-nu)** are a standard flux candle
- MINERvA **fit low-nu events to detector and beam parameters** to diagnose an apparent flux problem
- Result of the fit was that the problem was consistent with a small **muon energy scale shift**
- Potentially **useful technique for future experiments**
  - Using information about **transverse position** of events was particularly helpful



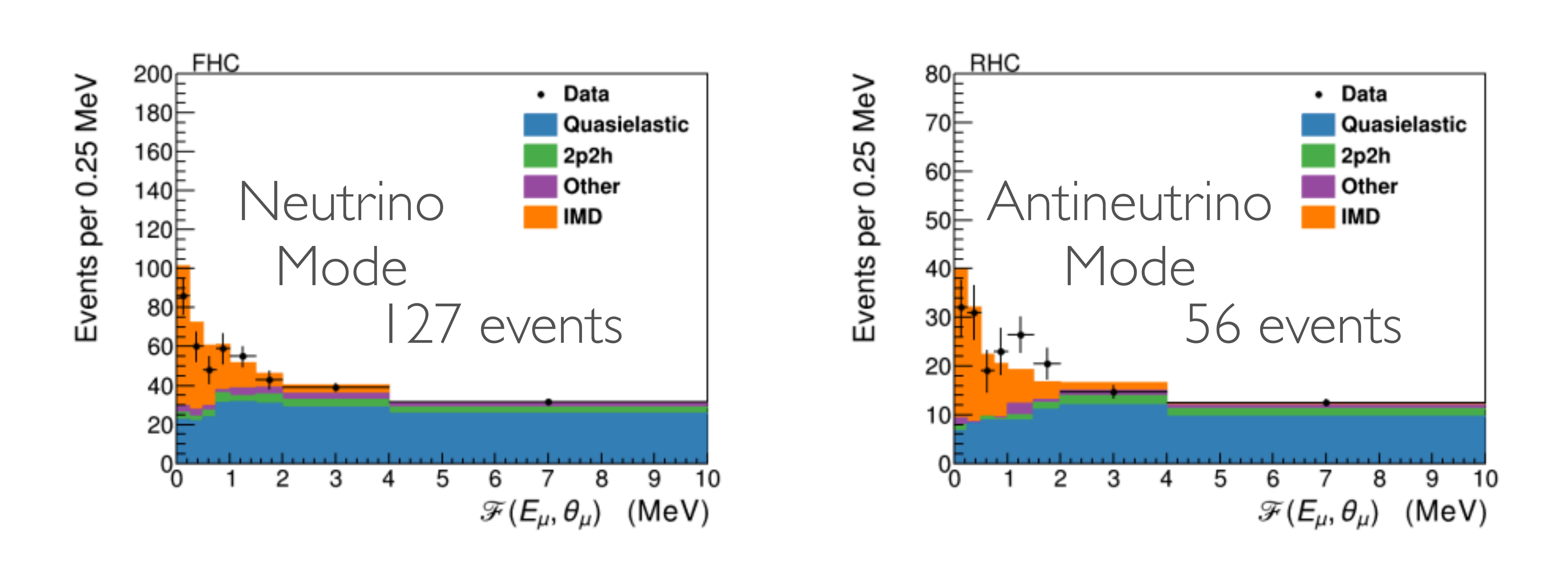


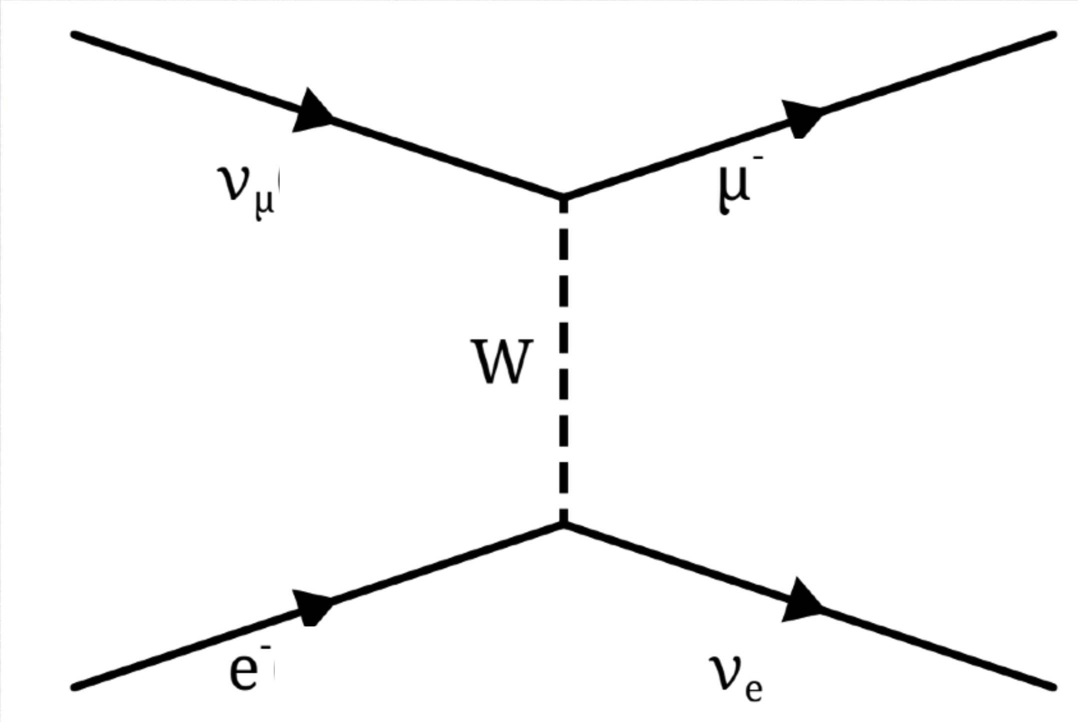




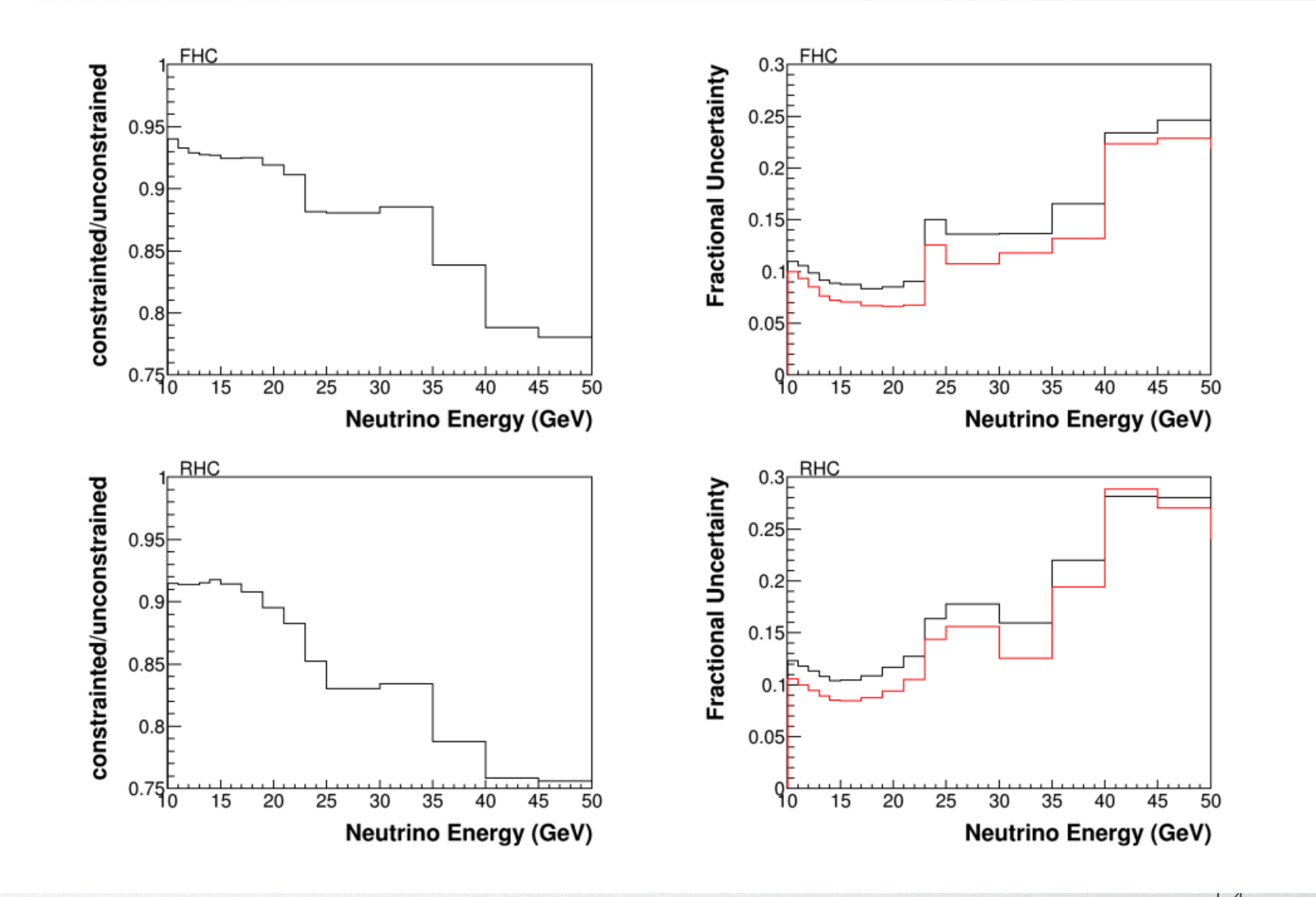
FLUX MEASUREMENTS: MINERVA

Phys. Rev. D 104, 092010 (2021)

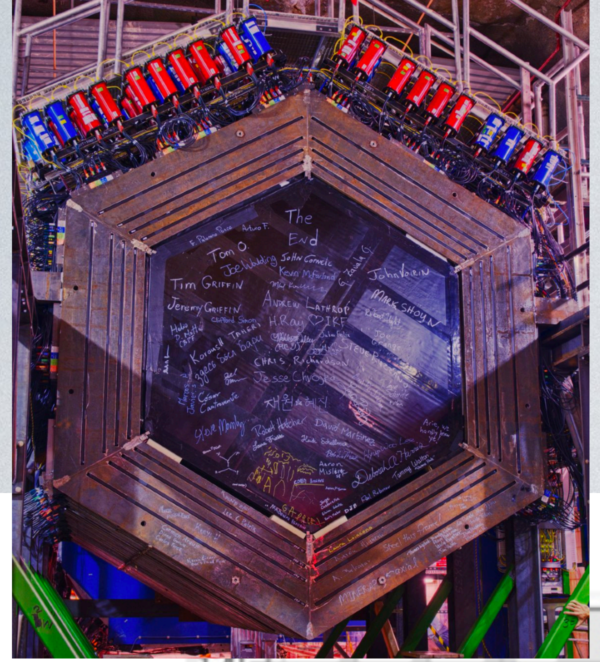




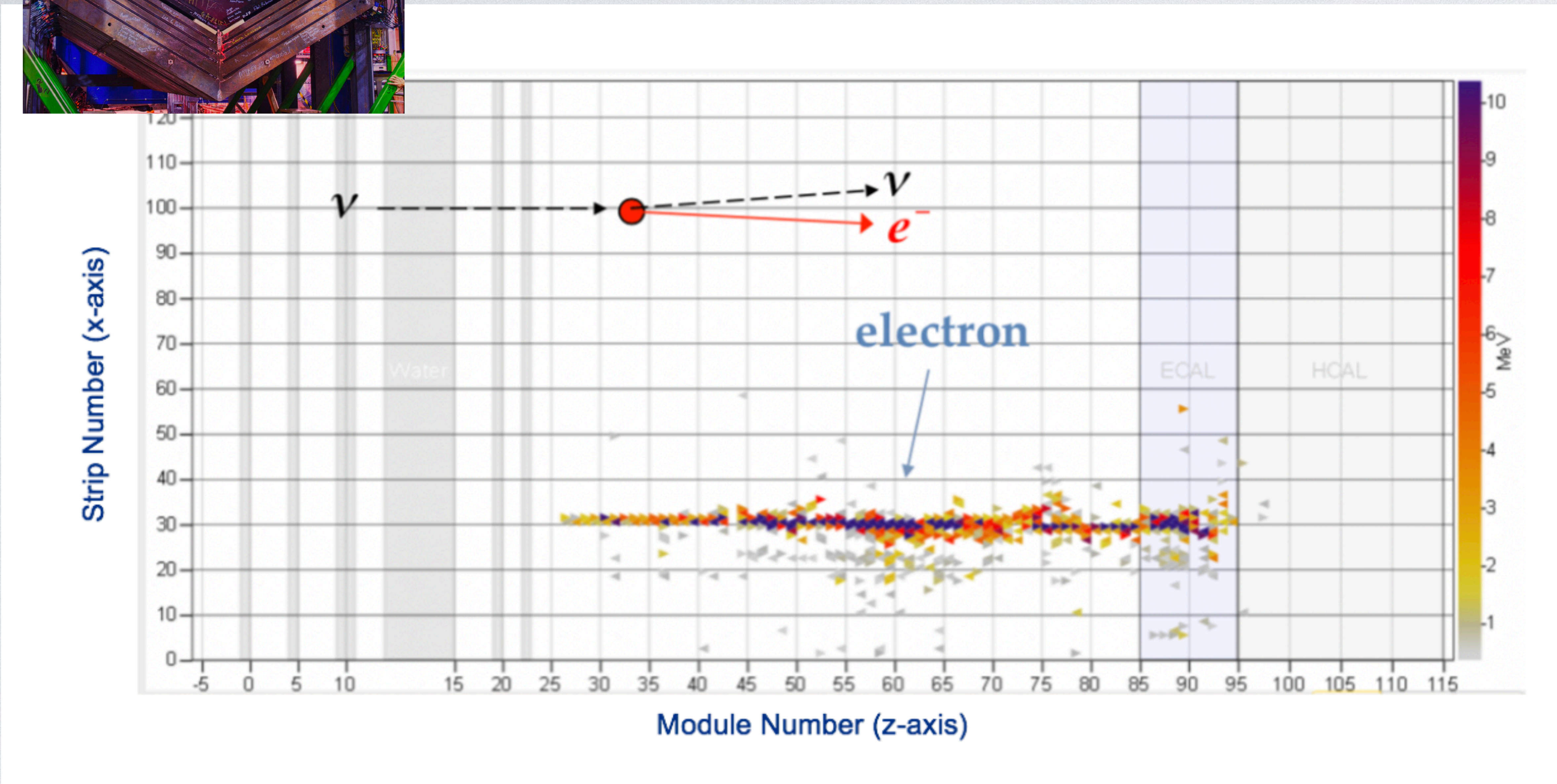
FLUX

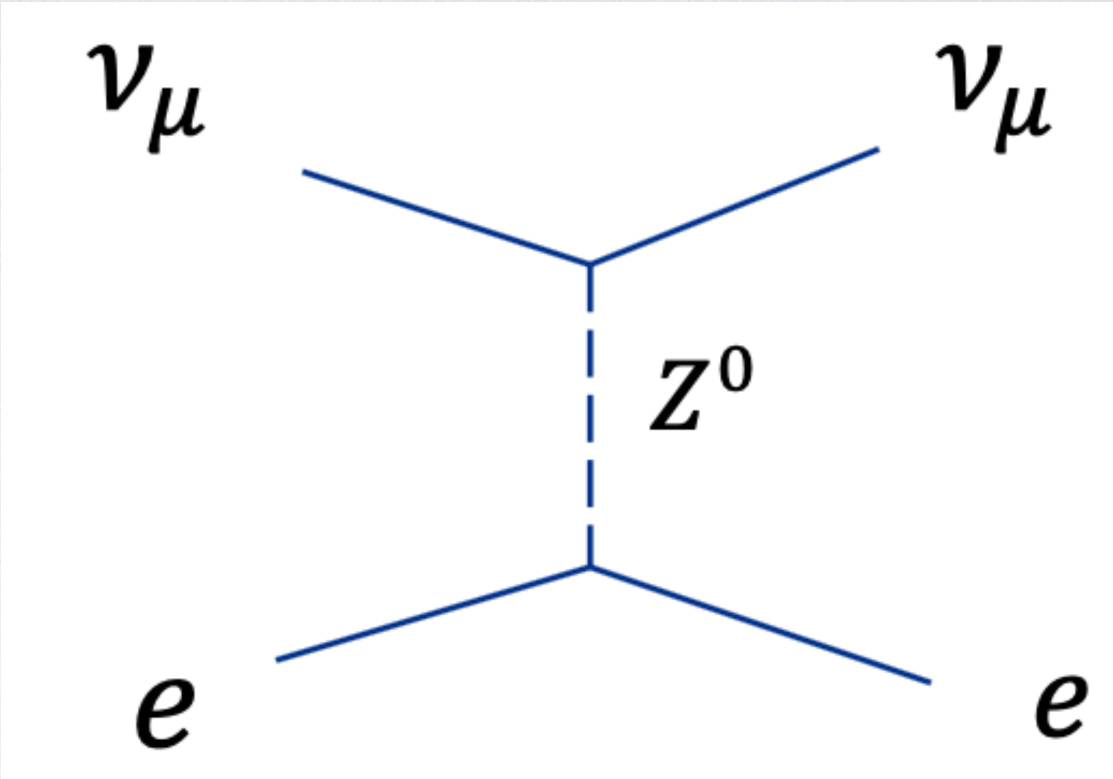


- MINERvA has also used **inverse muon decay** as a standard candle to measure the NuMI
  - **Constrains flux in high energy tail**



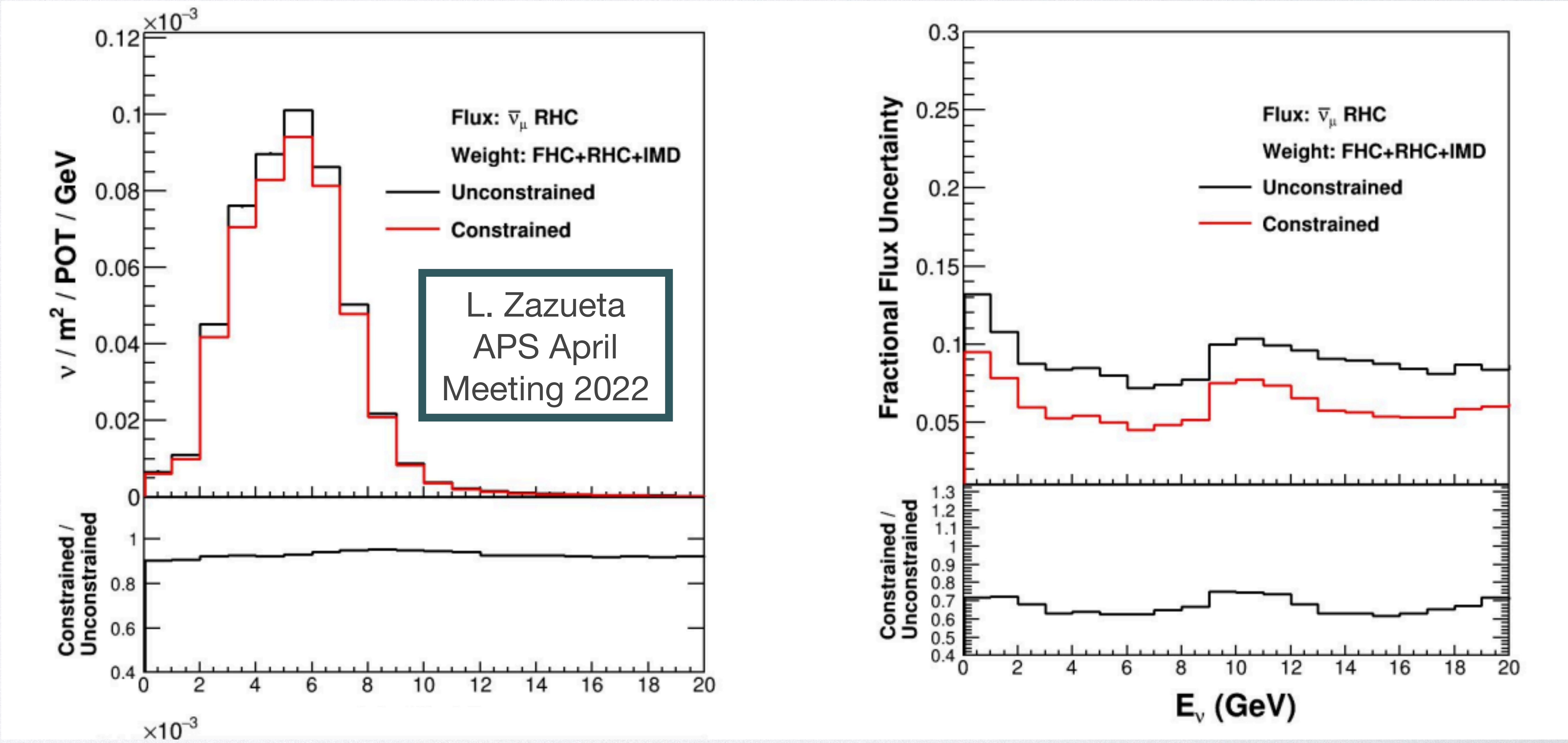
FLUX MEASUREMENTS: MINERVA



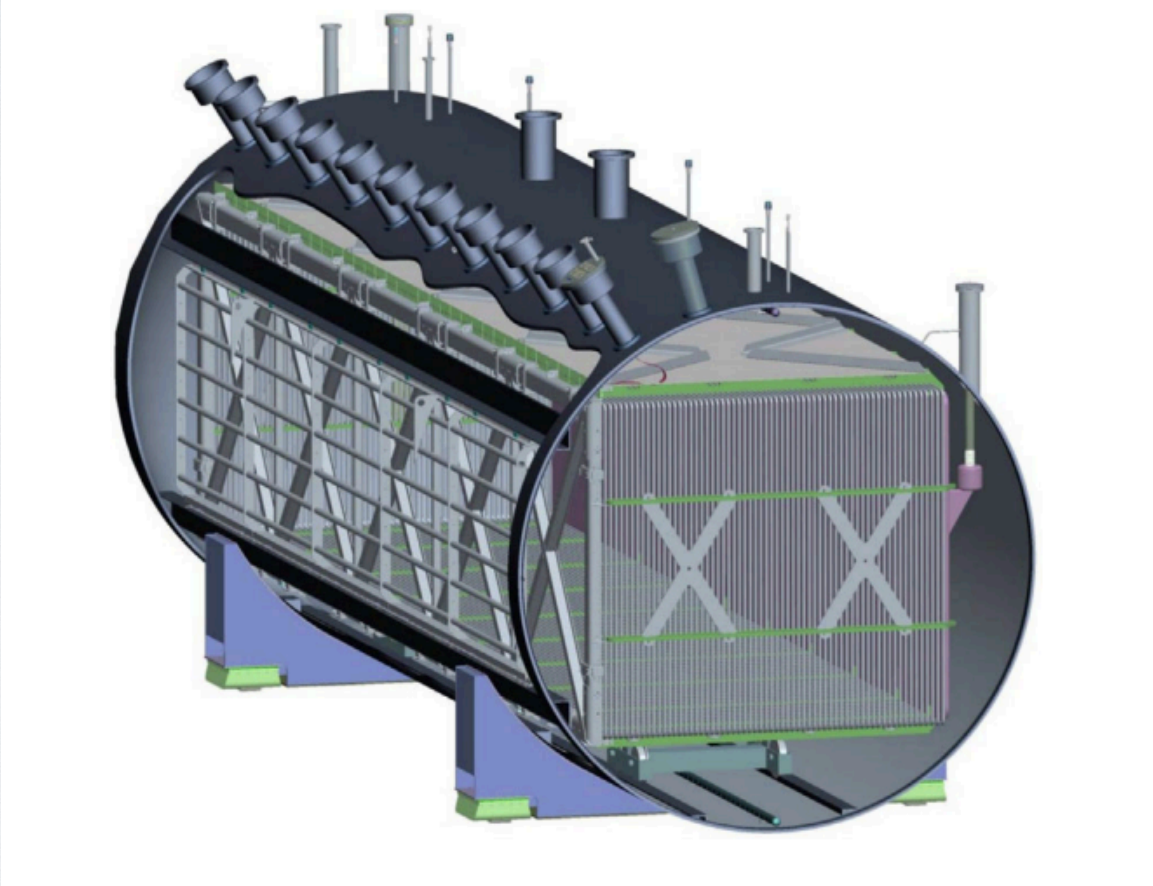


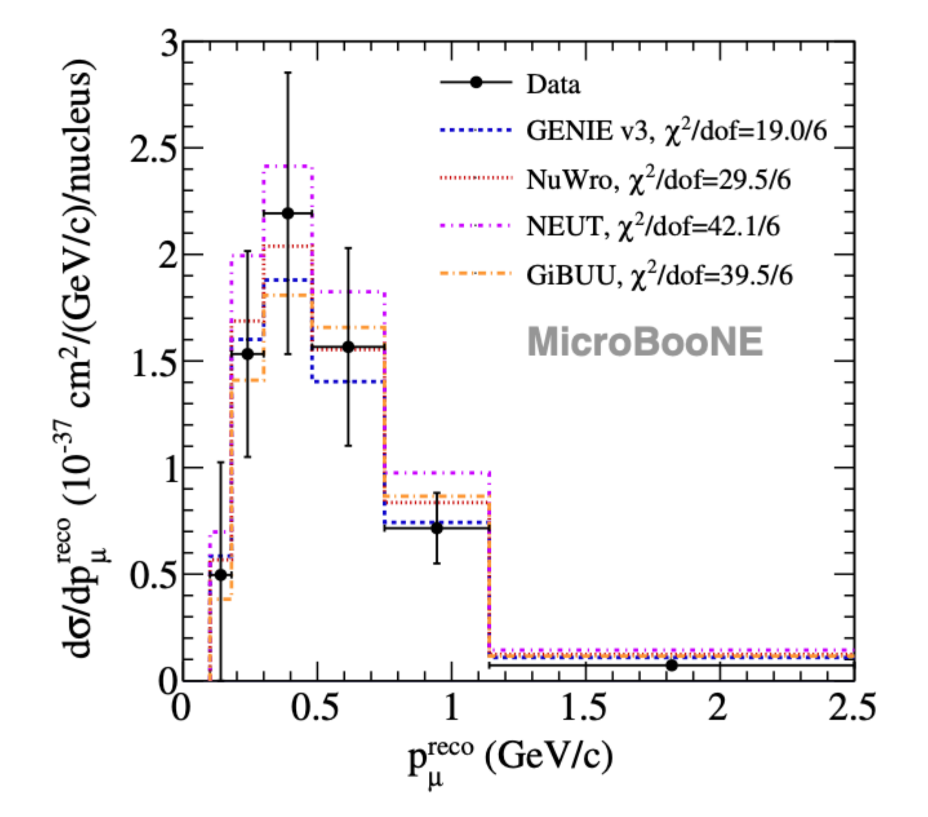
FLUX

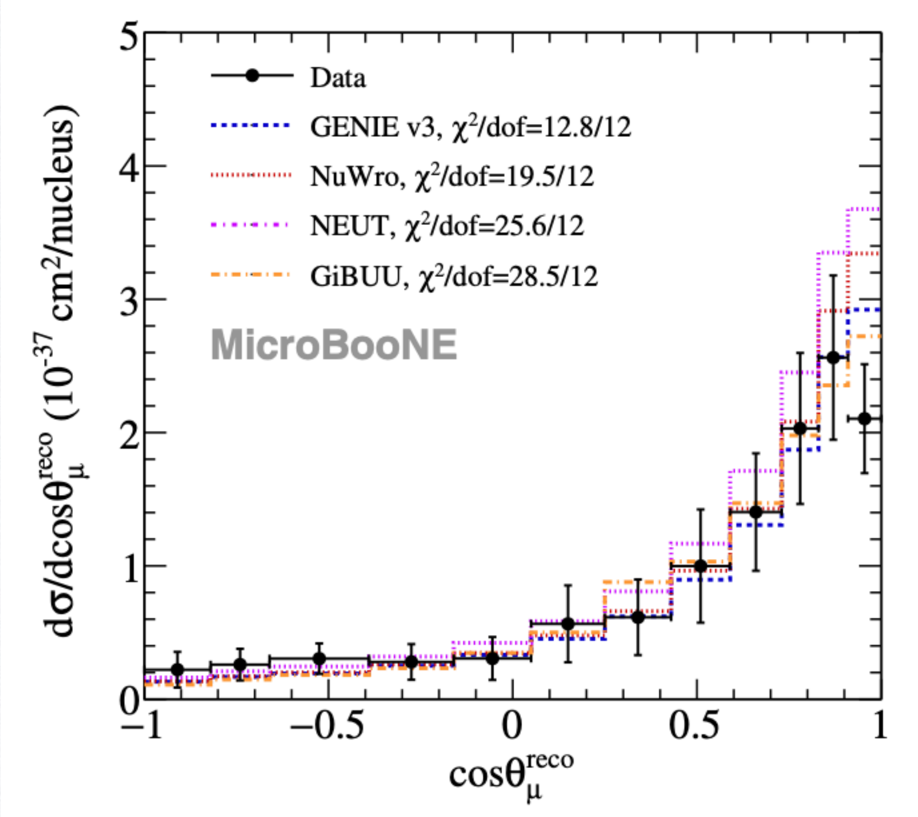
- MINERvA used **neutrino scattering on electrons** to measure flux in both neutrino and antineutrino mode (new)
- Combining **all flux constraints:**
  - **3.3% uncertainty in neutrino mode**
  - **4.7% uncertainty in antineutrino mode**



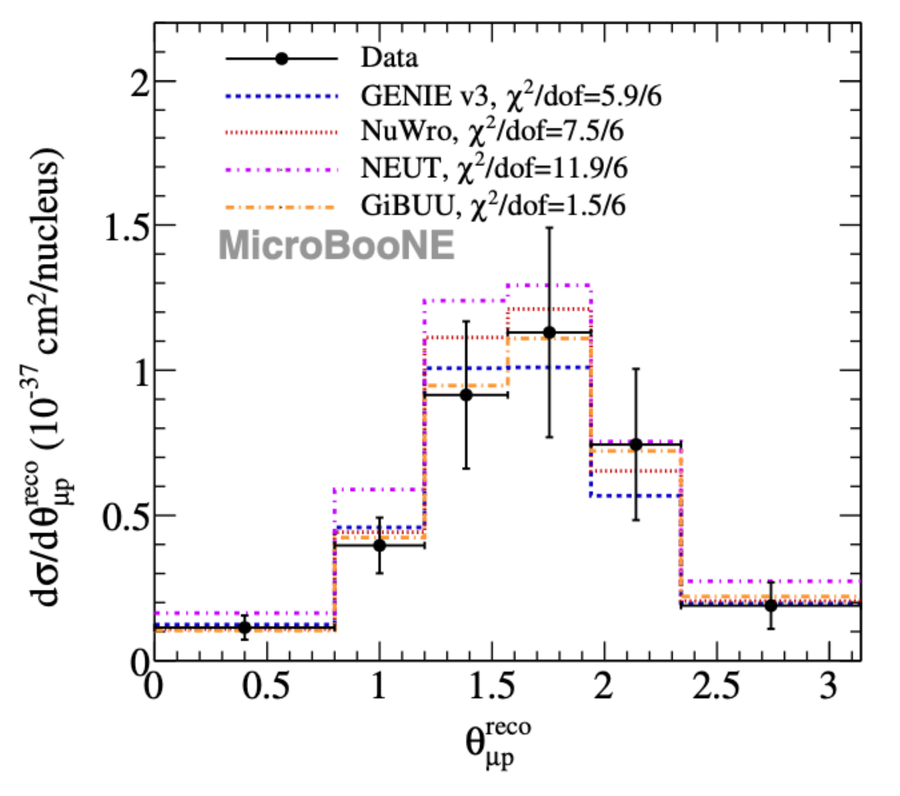
0PI: MICROBOONE

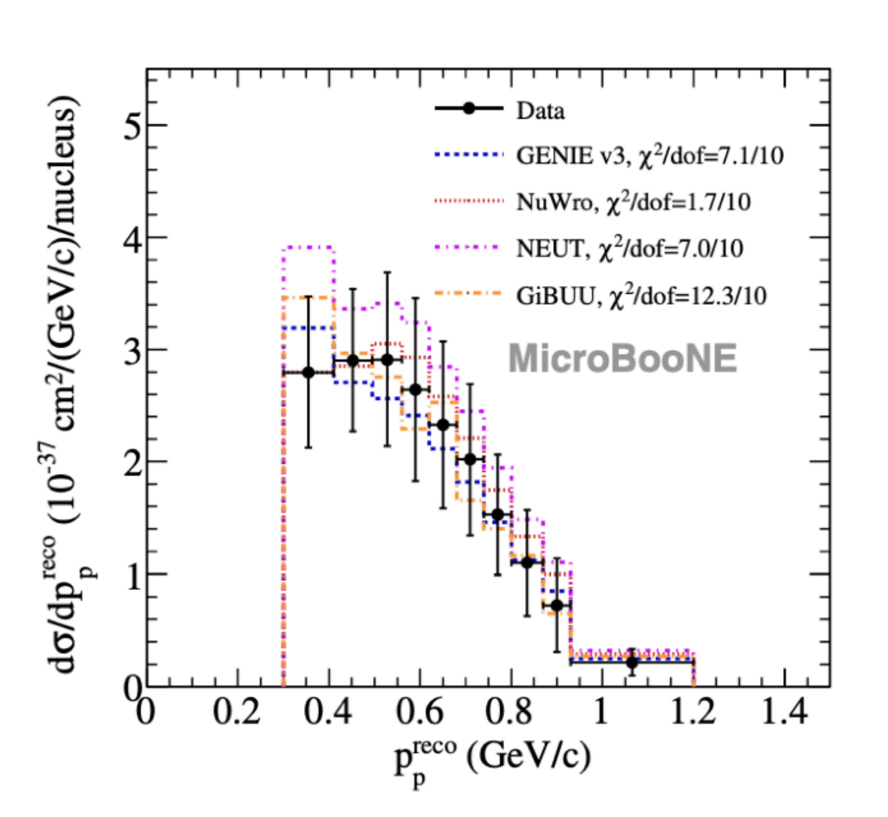


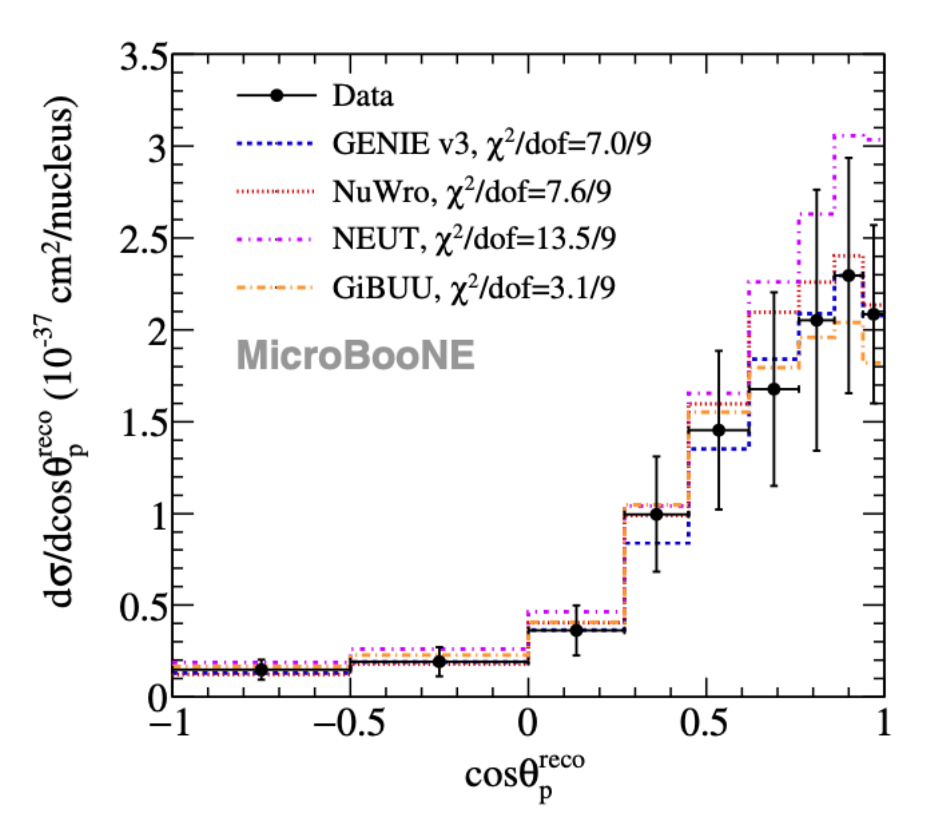




Phys. Rev. D 102, 112013





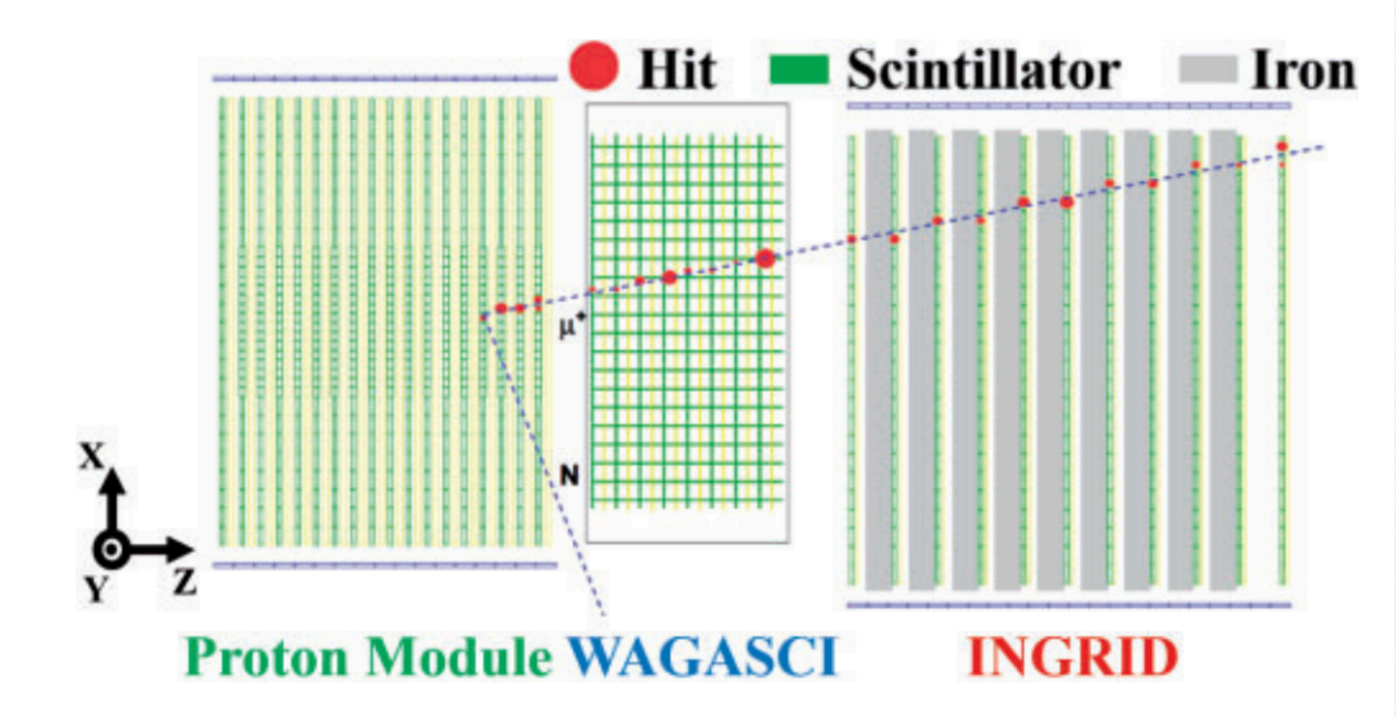


- **MicroBooNE** measurement of ν_μ **0piNp** interactions
- Cross sections versus **muon and proton kinematics and angle** between muon and proton
- Large uncertainties, but
  - Models over predict cross section at **forward muon angles**

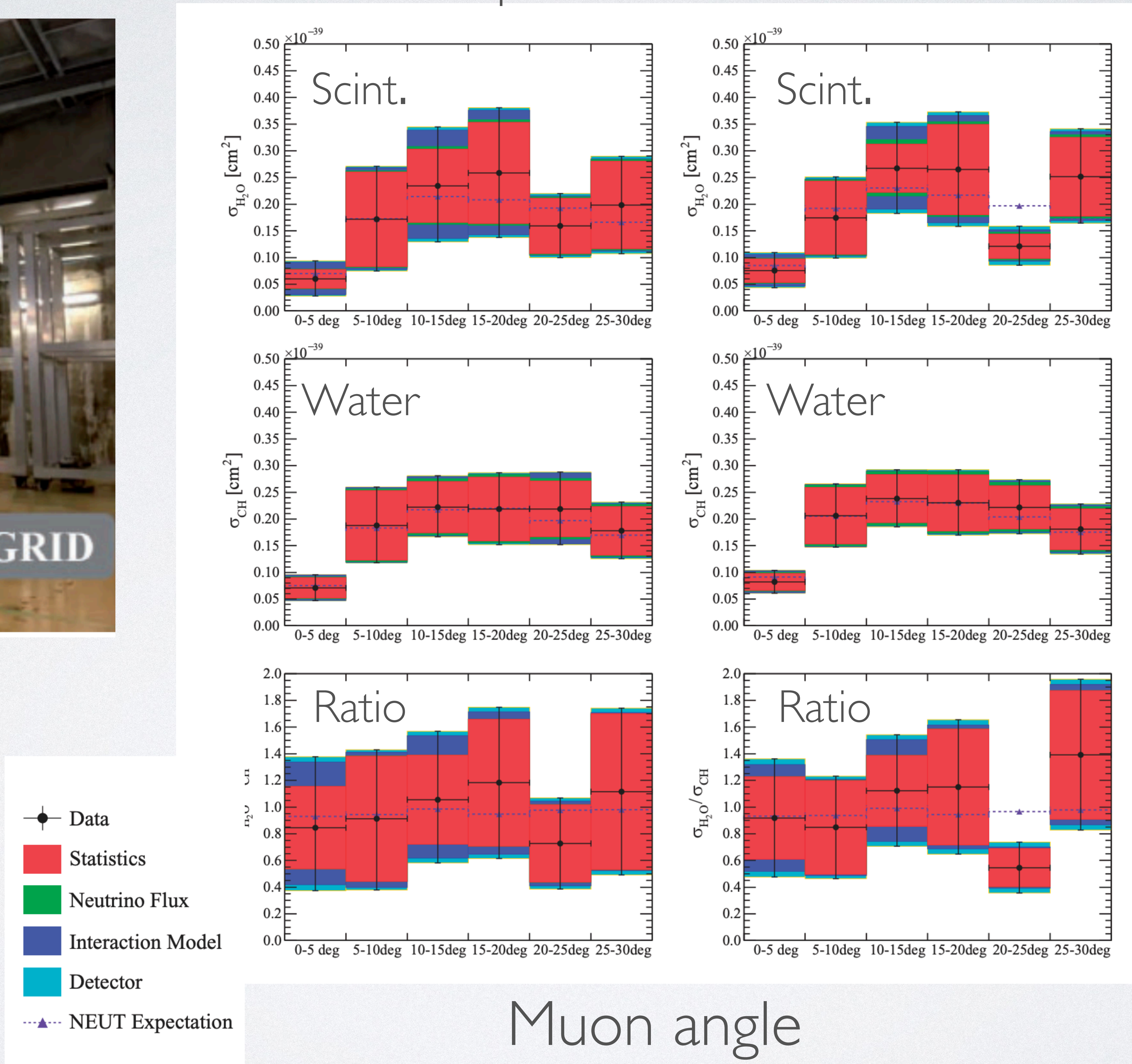
0PI:T2K

0π

Prog. Theor. Exp. Phys. 2021, 043C01

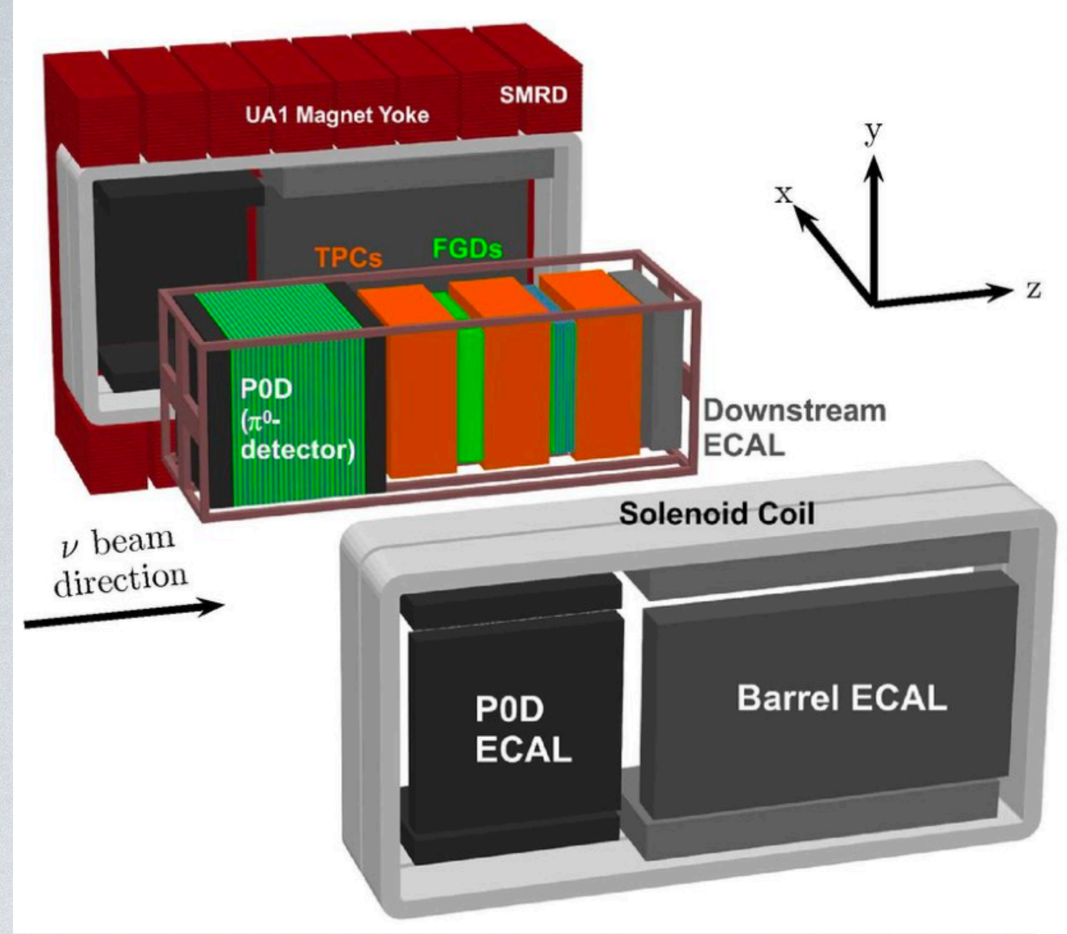


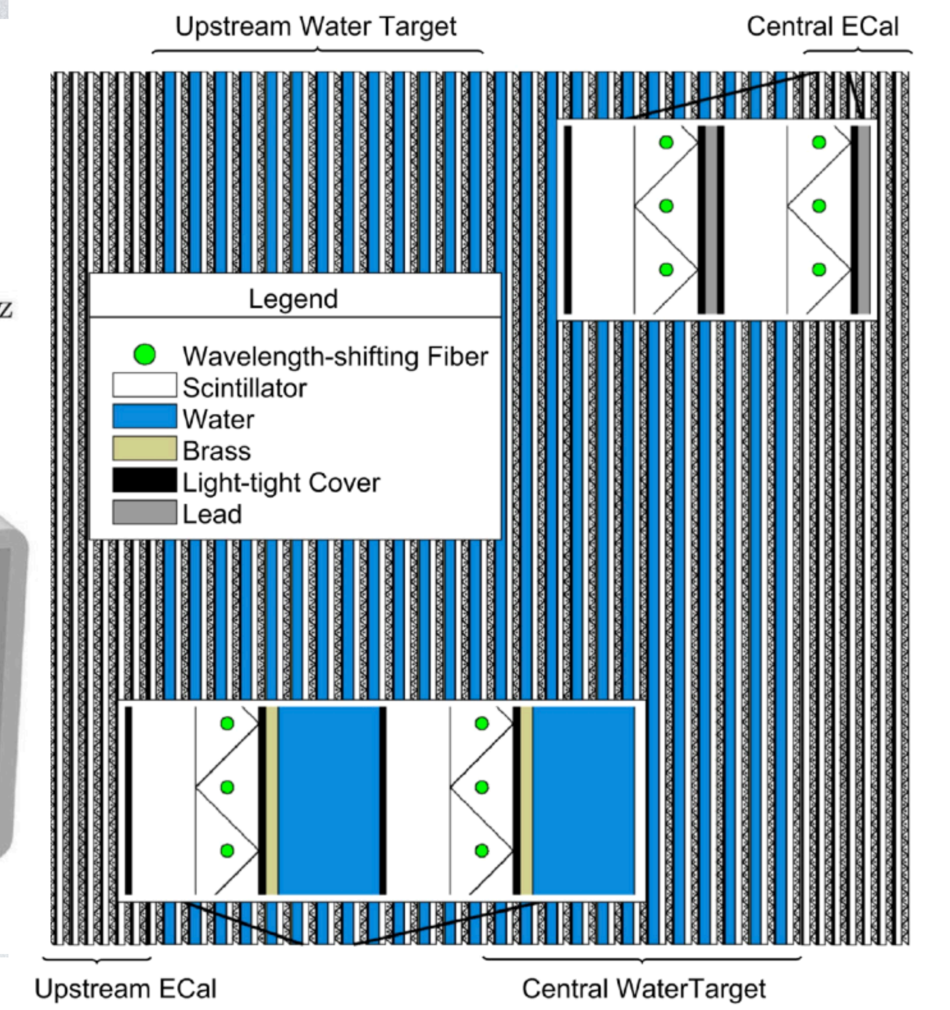
$\bar{\nu}_\mu$ | $\bar{\nu}_\mu + \nu_\mu$



Muon angle

- **T2K** measurement of **$\bar{\nu}_\mu$ 0π** on WAGASCI scintillator and water
- Compared only to **NEUT model** used for T2K oscillation analysis
- **Good agreement** within uncertainties

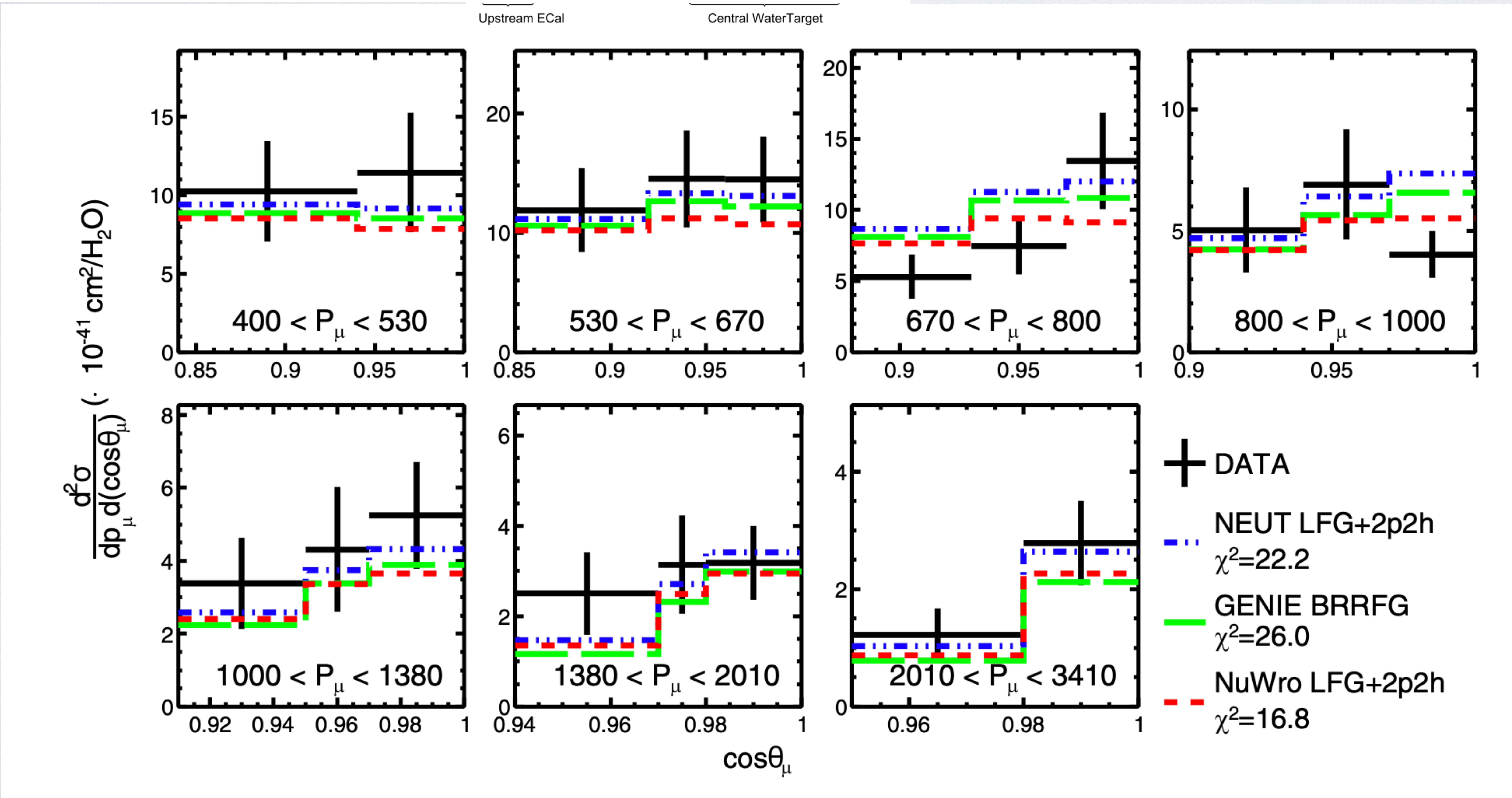




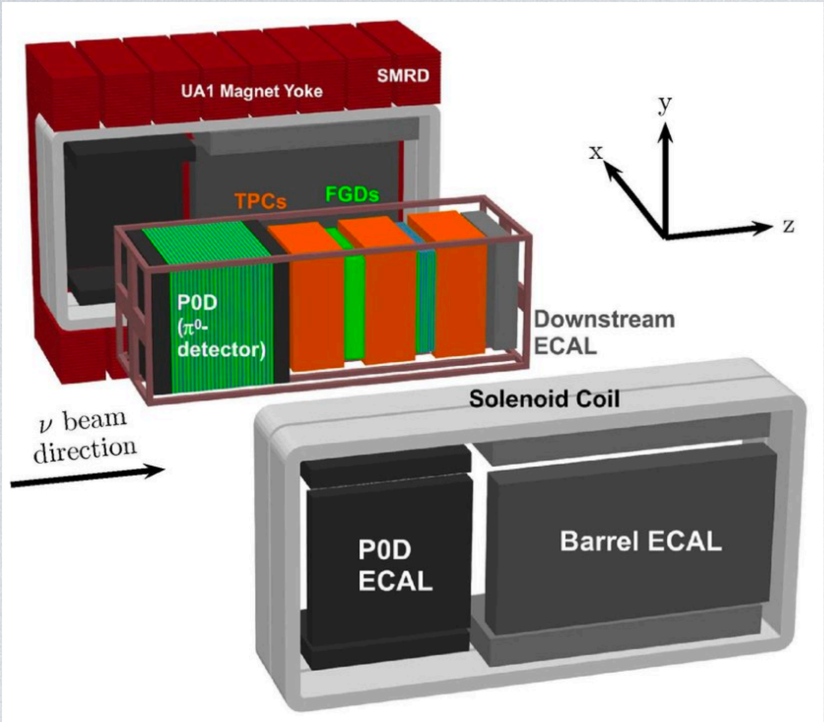
0PI:T2K

0π

Phys. Rev. D 102, 012007 (2020)



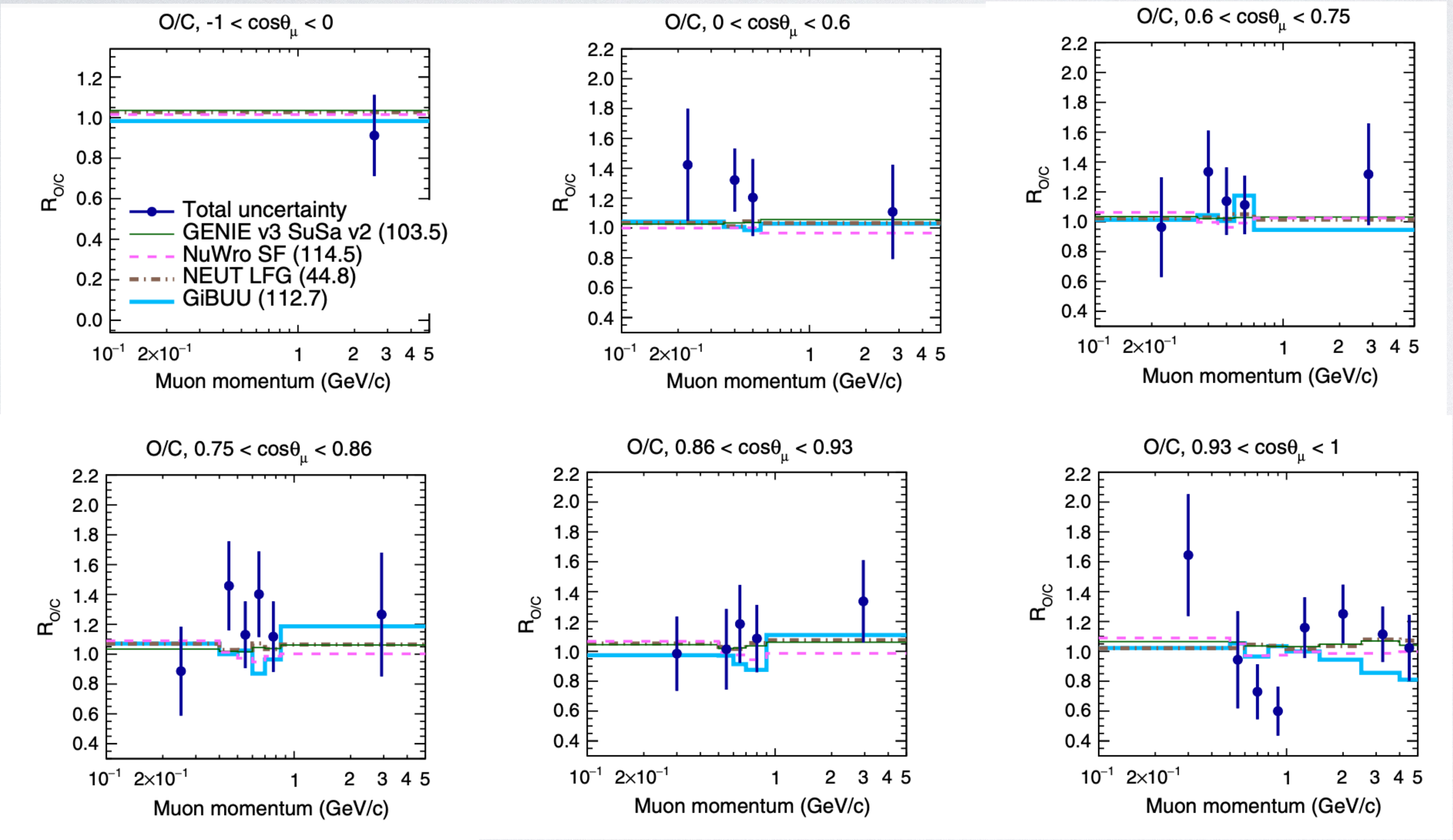
- New **T2K $\bar{\nu}_\mu$ 0π** on water using the ND280 PØD detector
- **Double differential muon kinematics** cross sections
- **Good agreement** within uncertainties with all models; **best agreement with NuWro LFG+2p2h**



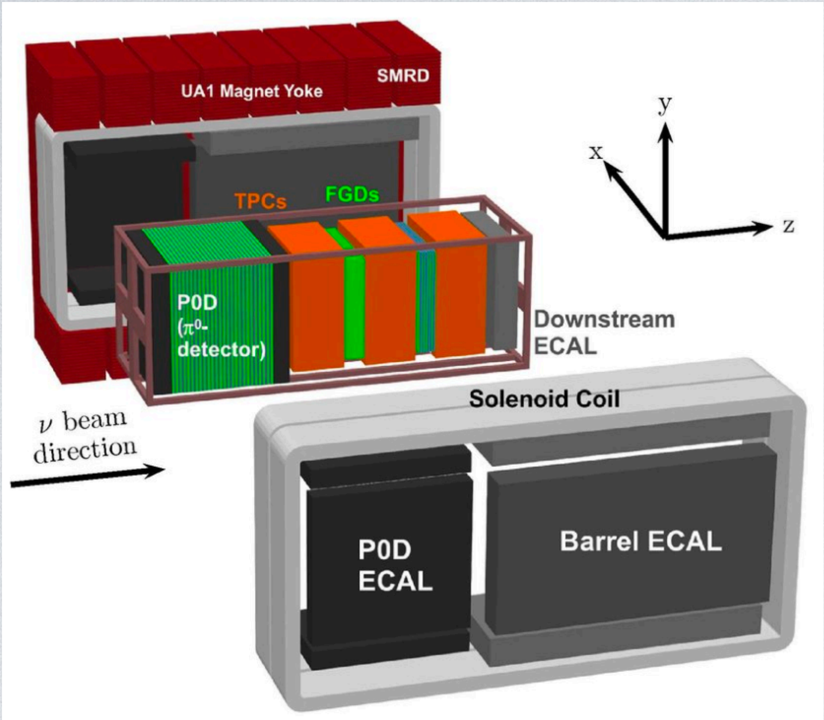
0PI:T2K

0π

Phys. Rev. D 101, 112004



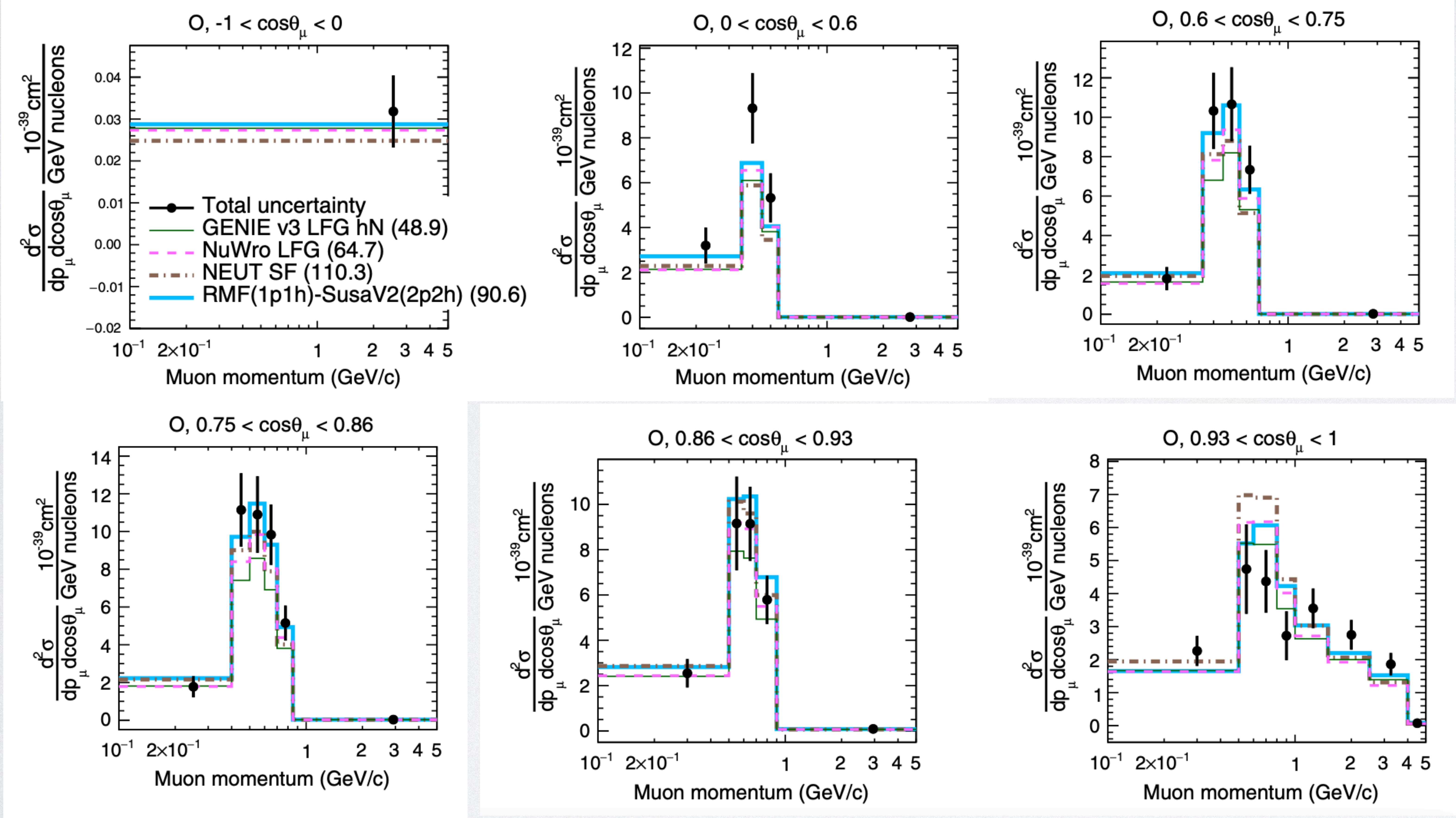
- **T2K ν_μ CC 0π** on C and O ratios
- **All models agree well with ratio** within statistically-dominated uncertainties
- Individual cross section measurements on C and O: **preference for LFG+2p2h+RPA** suppression, primarily due to most **forward muon bins**



0PI:T2K

0π

Phys. Rev. D 101, 112004



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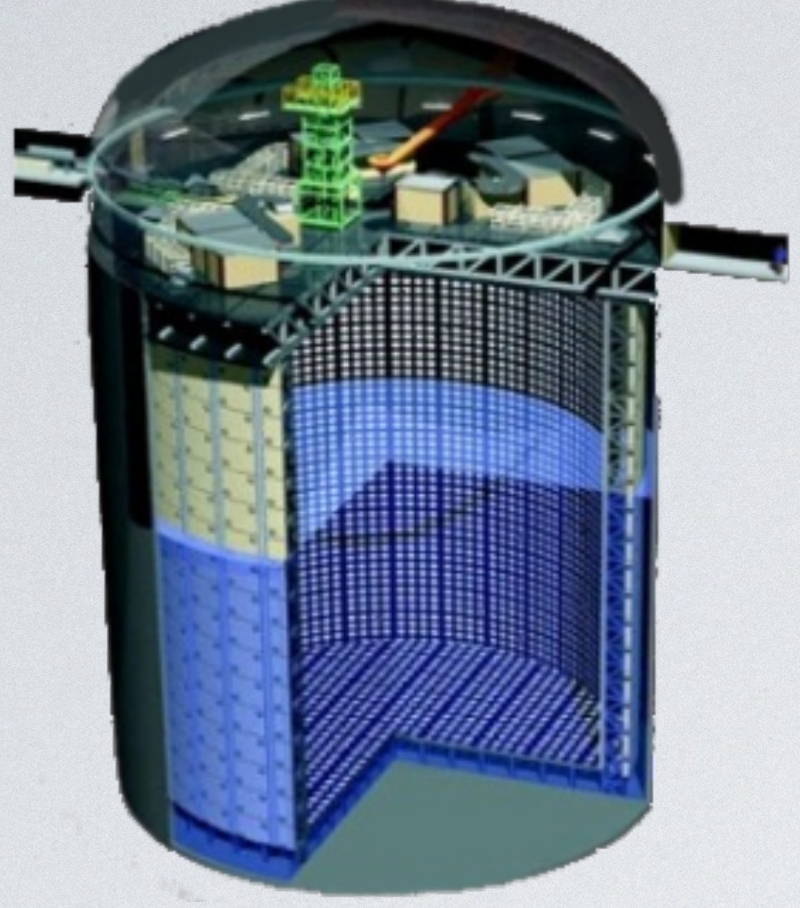
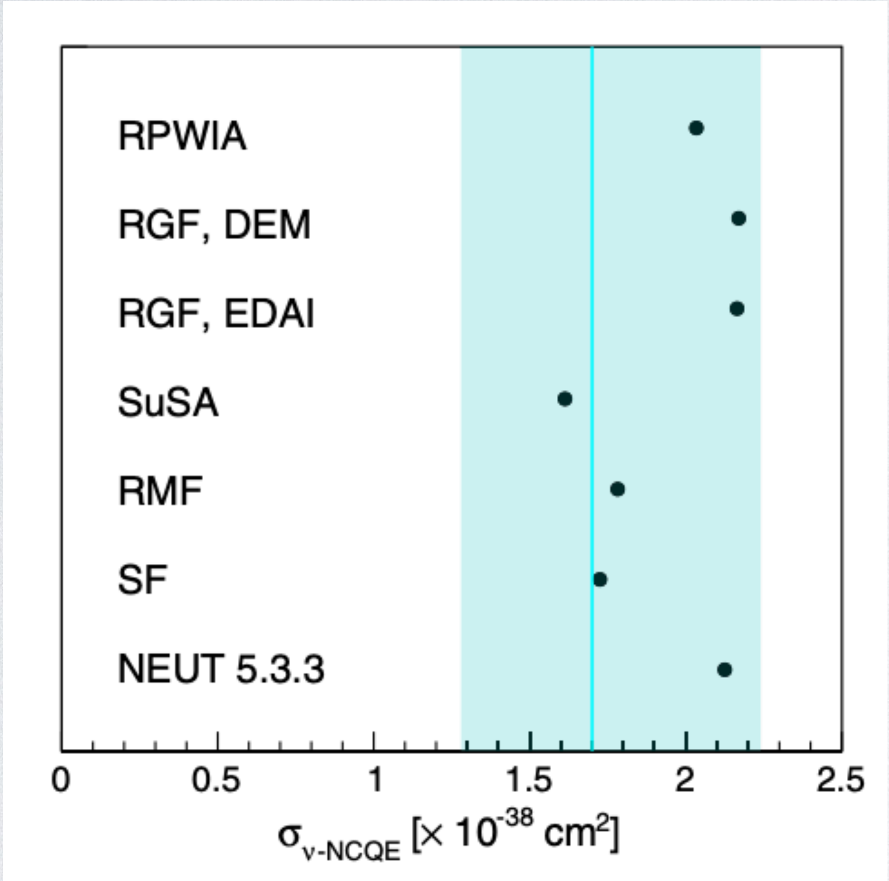
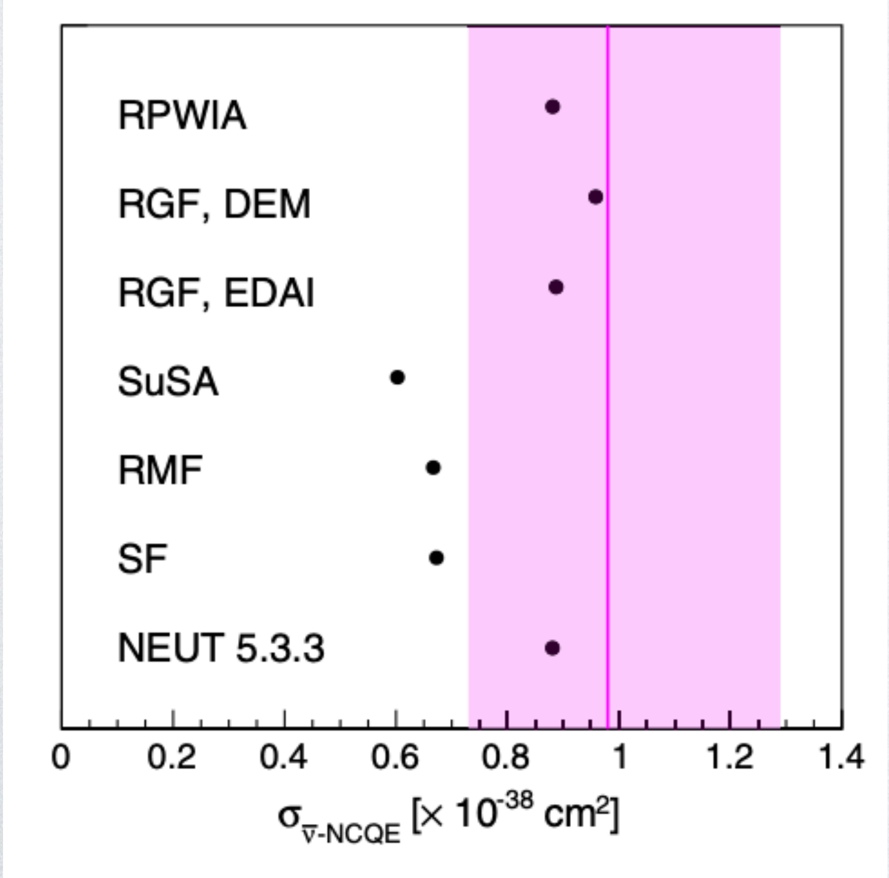
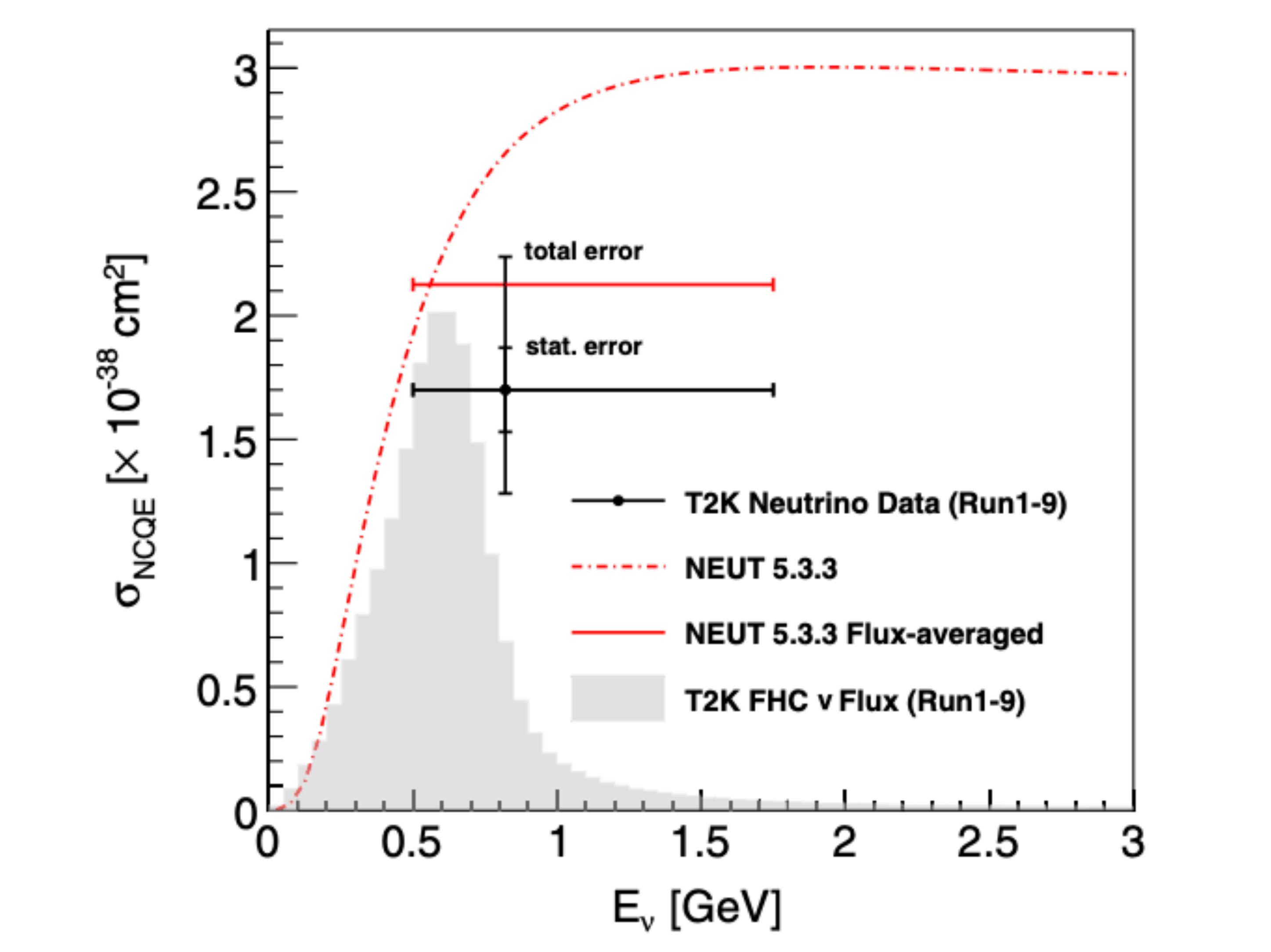
NC ELASTIC: T2K

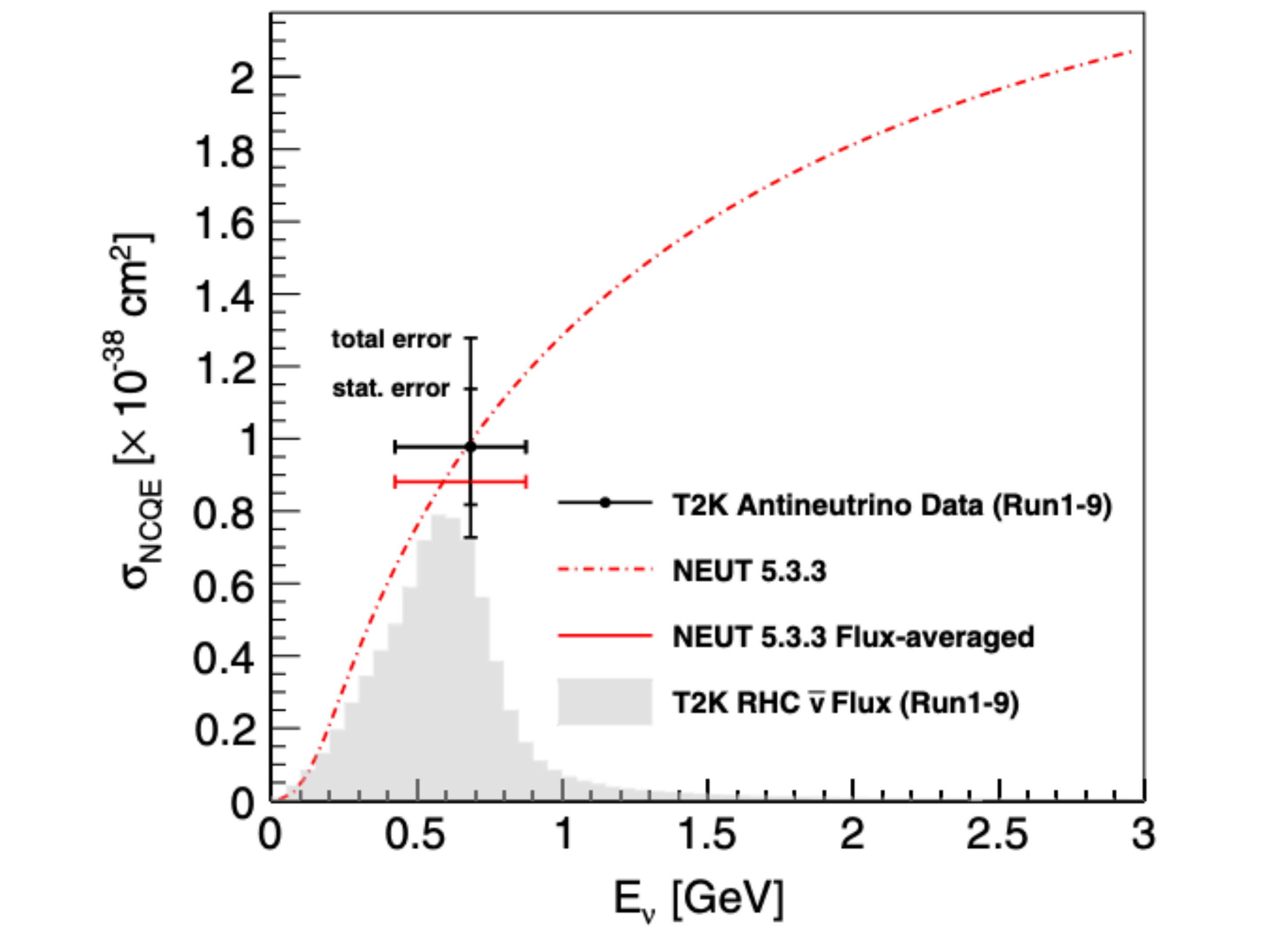
Phys. Rev. D **100**, 112009







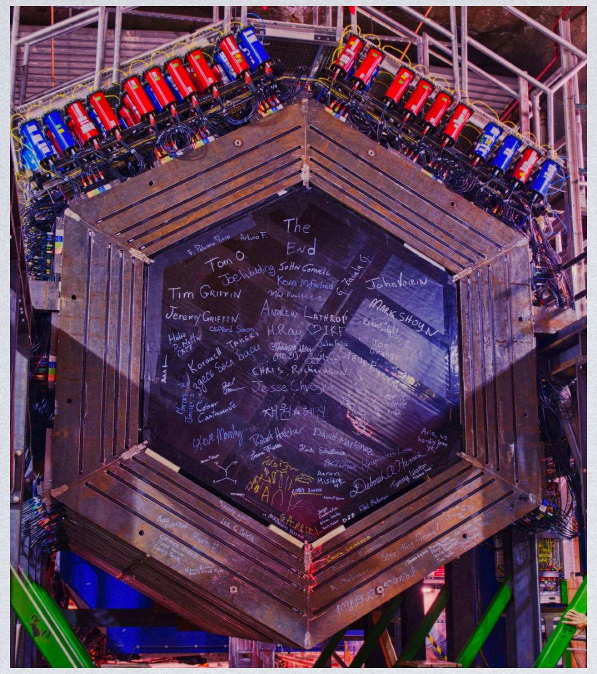




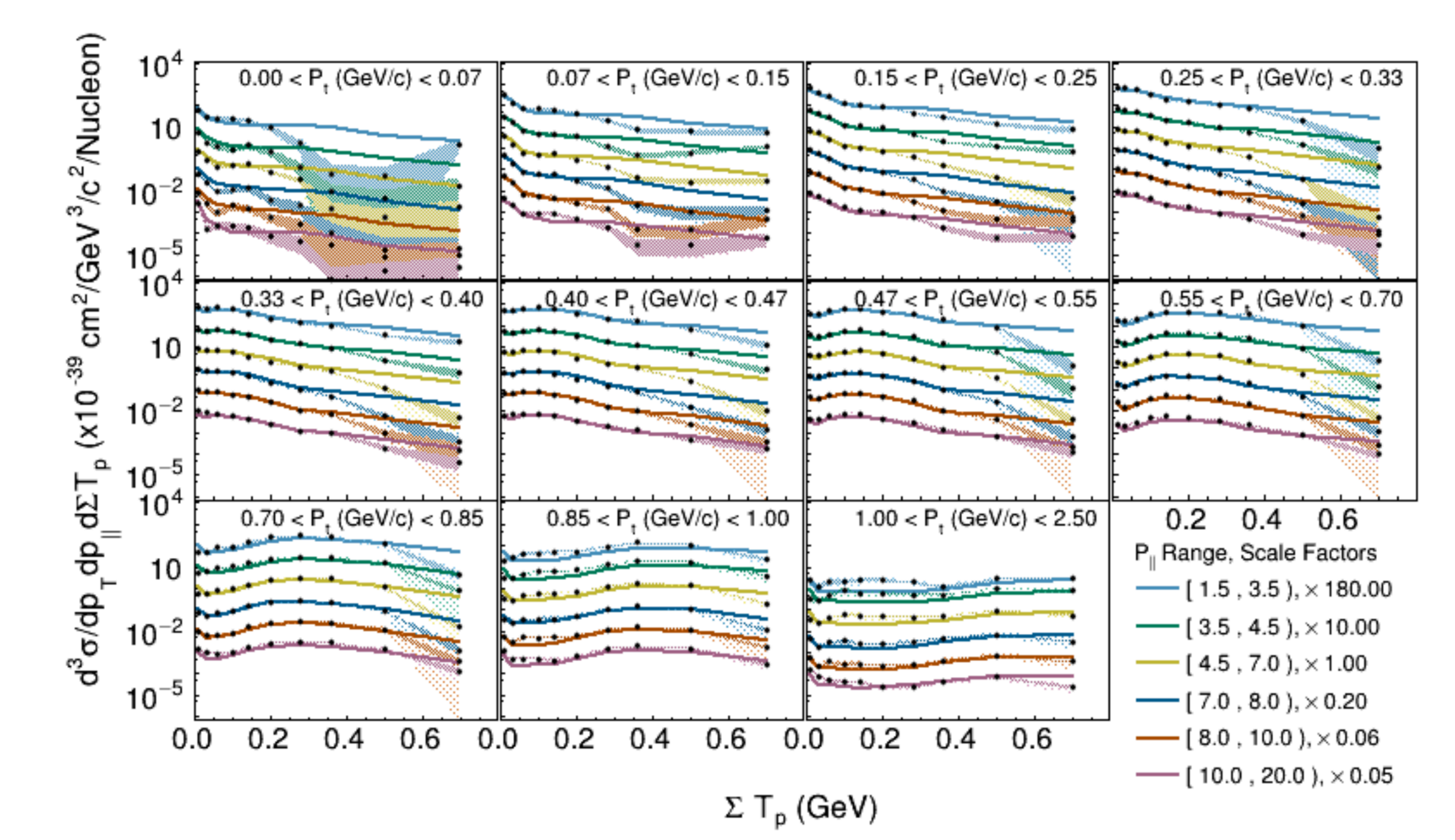
- **T2K ν+ν̄ NC elastic** cross section with far detector
  - Using **de-exitation photons**
- Atmospheric neutrino NC Elastic is **background to supernova relic neutrino** searches
- **All models agree** reasonably well with data
  - Interesting because **no NC 2p2h model** is available

0PI: MINERVA

0π

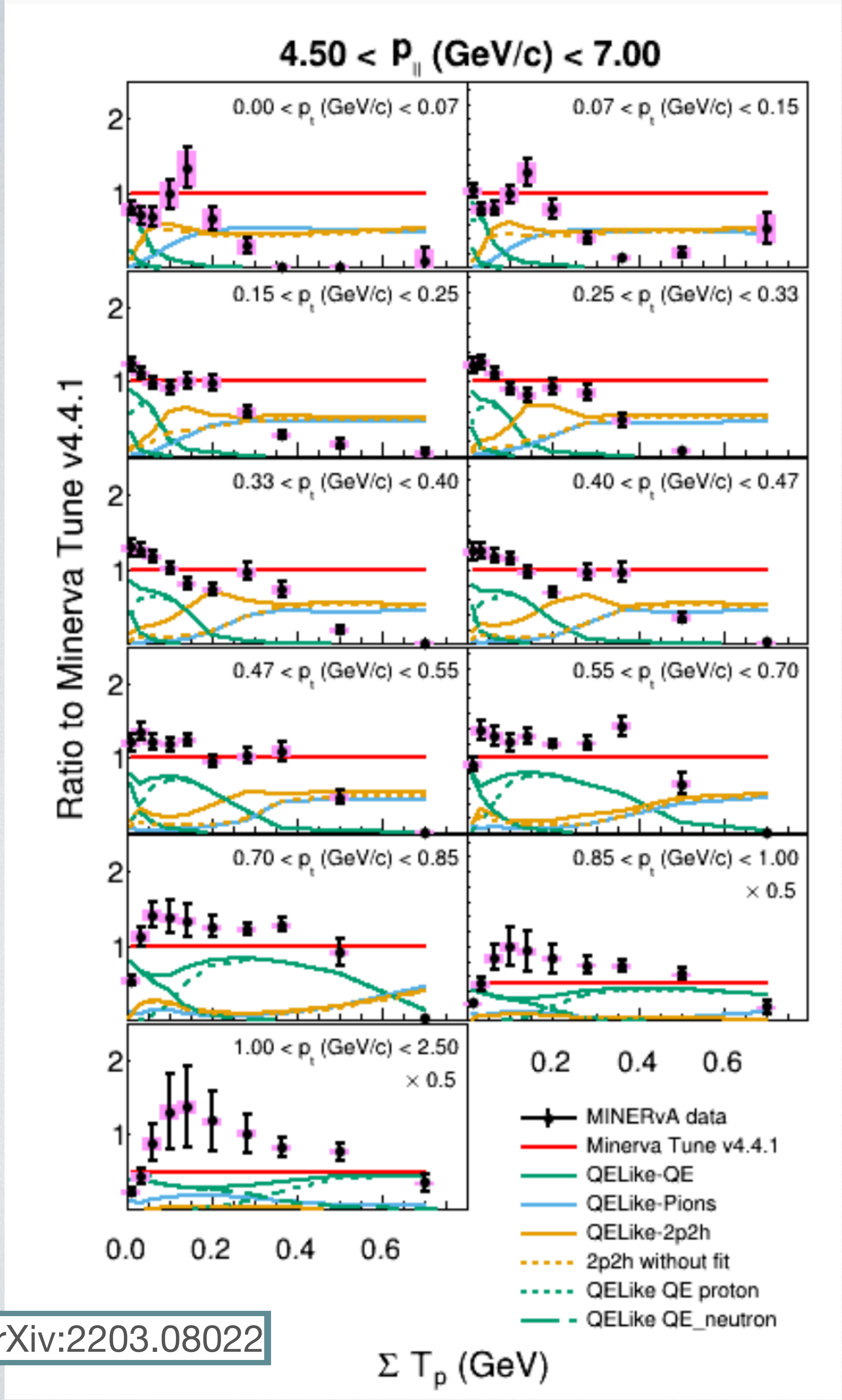


arXiv:2203.08022



Colored band show data uncertainties

- **MINERvA ν_μ 0π** on scintillator in 3D
  - **Transverse and longitudinal muon momentum**
  - **Total proton kinetic energy**
- **Excellent statistics** rarely seen in neutrino experiments!



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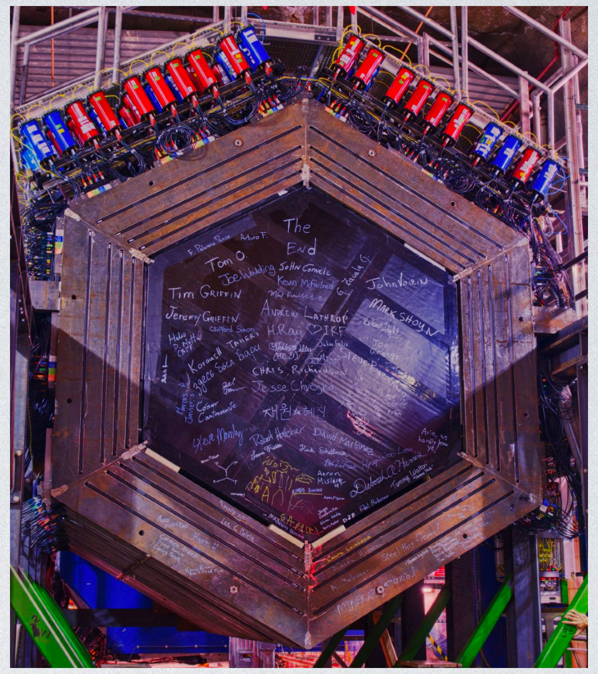
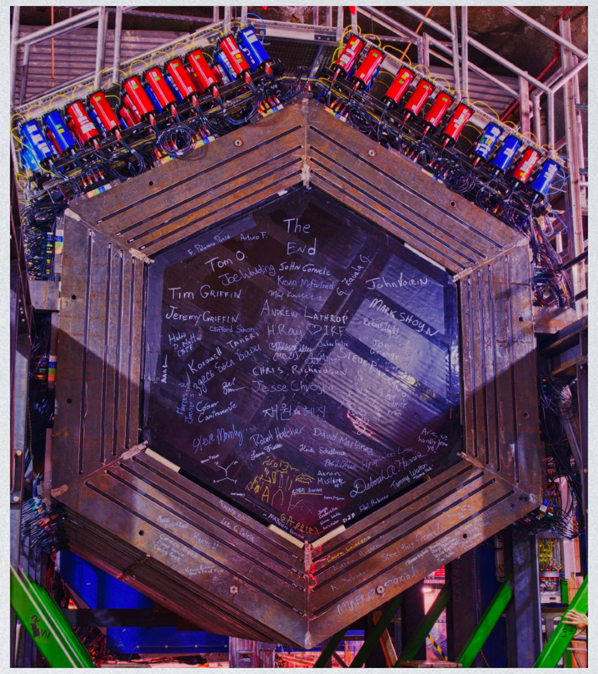
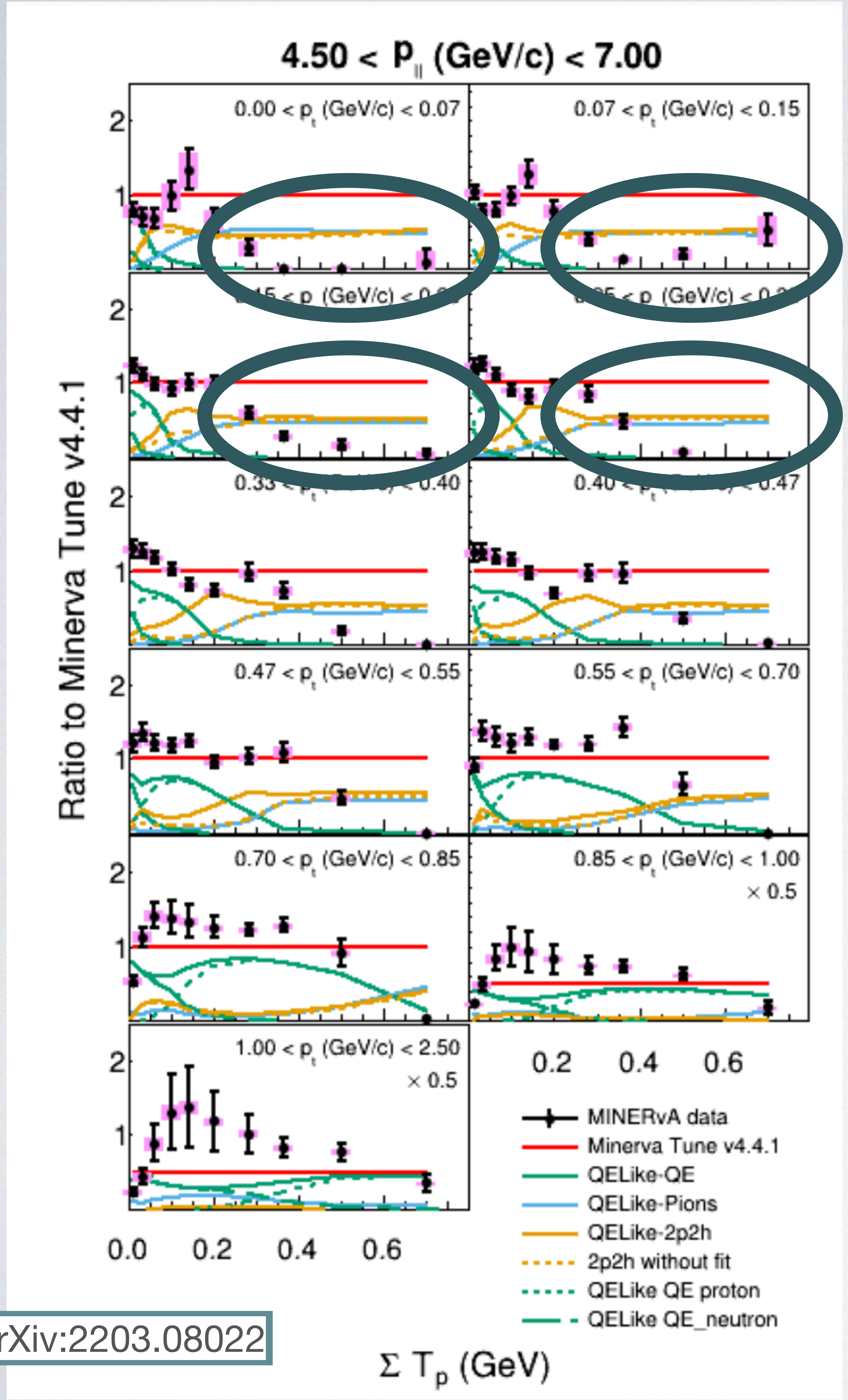
0PI: MINERVA



- Three key regions:
  - **Low muon pT, high proton kinetic energy**
    - **Few events in data where simulation predicts 2p2h, resonant + pion absorption**
  - **Proton kinetic energy near 0.2 GeV**
    - **Low Pt: relatively good agreement with MINERvA 2p2h tune**
    - **High Pt: Tune not sufficient at high Pt**
  - **High Pt, low Tp:**
    - ***over prediction in data in a region dominated by QE with FSI***

0PI: MINERVA





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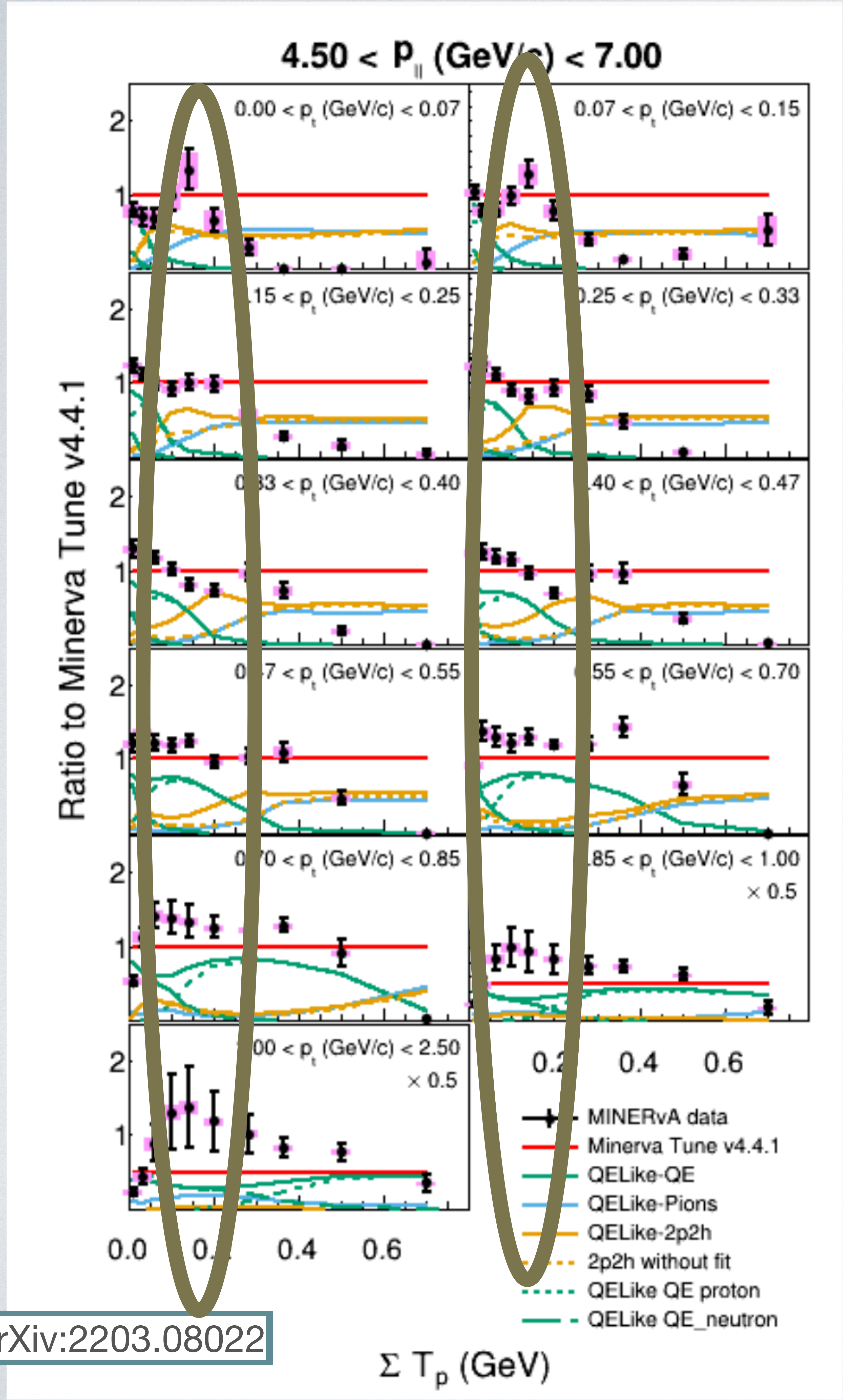
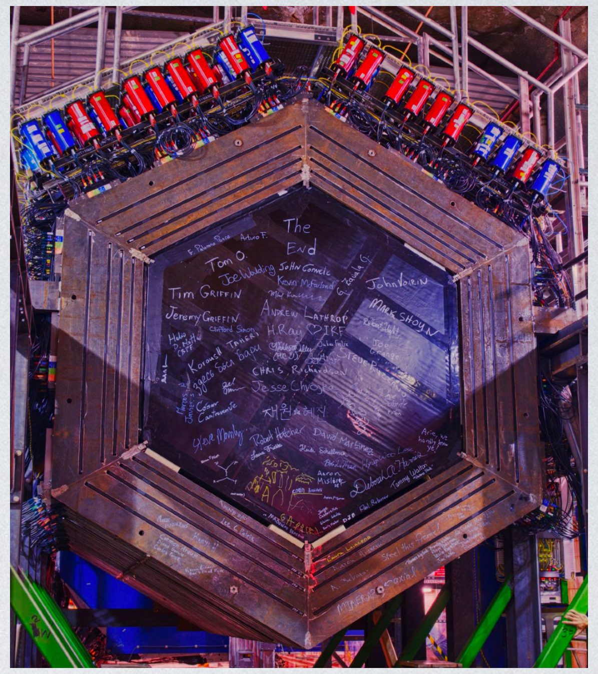
  - **Proton kinetic energy near 0.2 GeV**
    - **Low Pt: relatively good agreement with MINERvA 2p2h tune**
    - **High Pt: Tune not sufficient at high Pt**
  - **High Pt, low Tp:**
    - ***over prediction in data in a region dominated by QE with FSI***

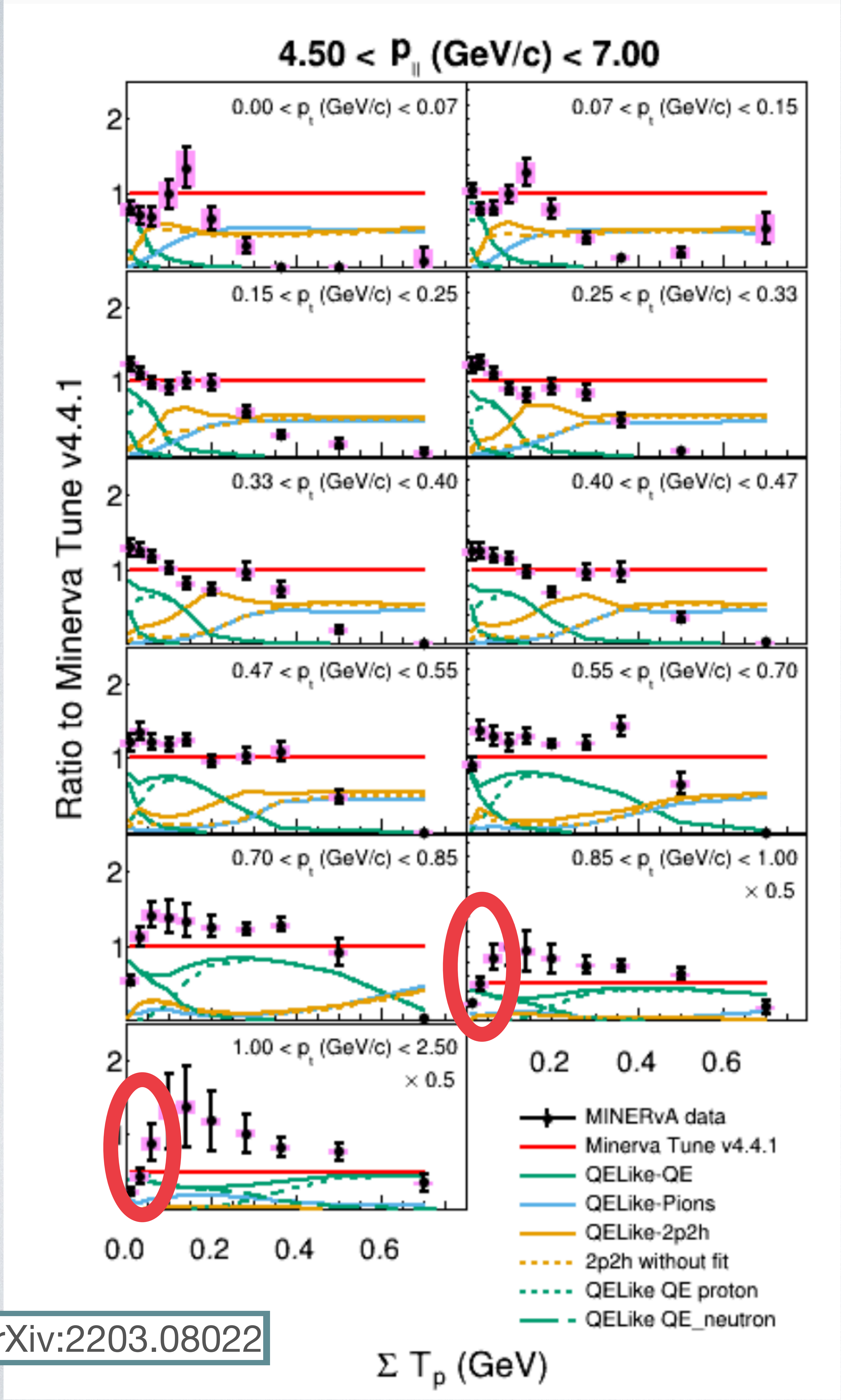
0PI: MINERVA



arXiv:2203.08022

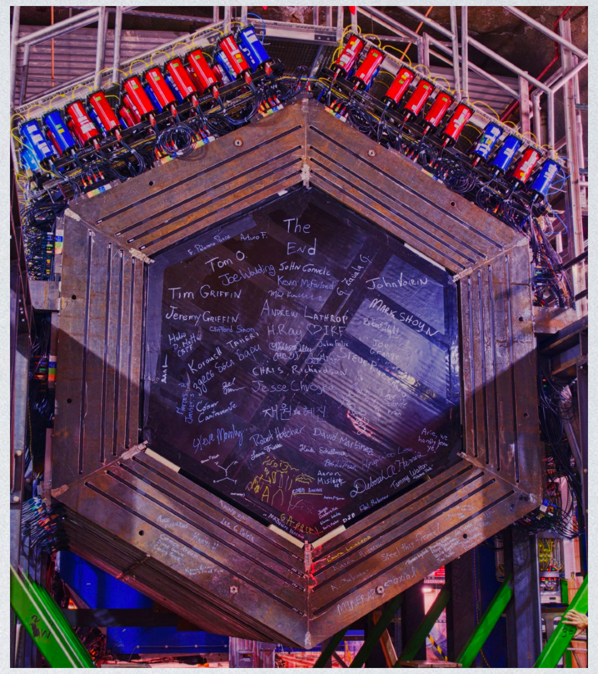


- Three key regions:
  - **Low muon pT, high proton kinetic energy**
    - **Few events in data where simulation predicts 2p2h, resonant + pion absorption**
  - **Proton kinetic energy near 0.2 GeV**
    - **Low Pt: relatively good agreement with MINERvA 2p2h tune**
    - **High Pt: Tune not sufficient at high Pt**
  - **High Pt, low Tp:**
    - ***over prediction in data in a region dominated by QE with FSI***



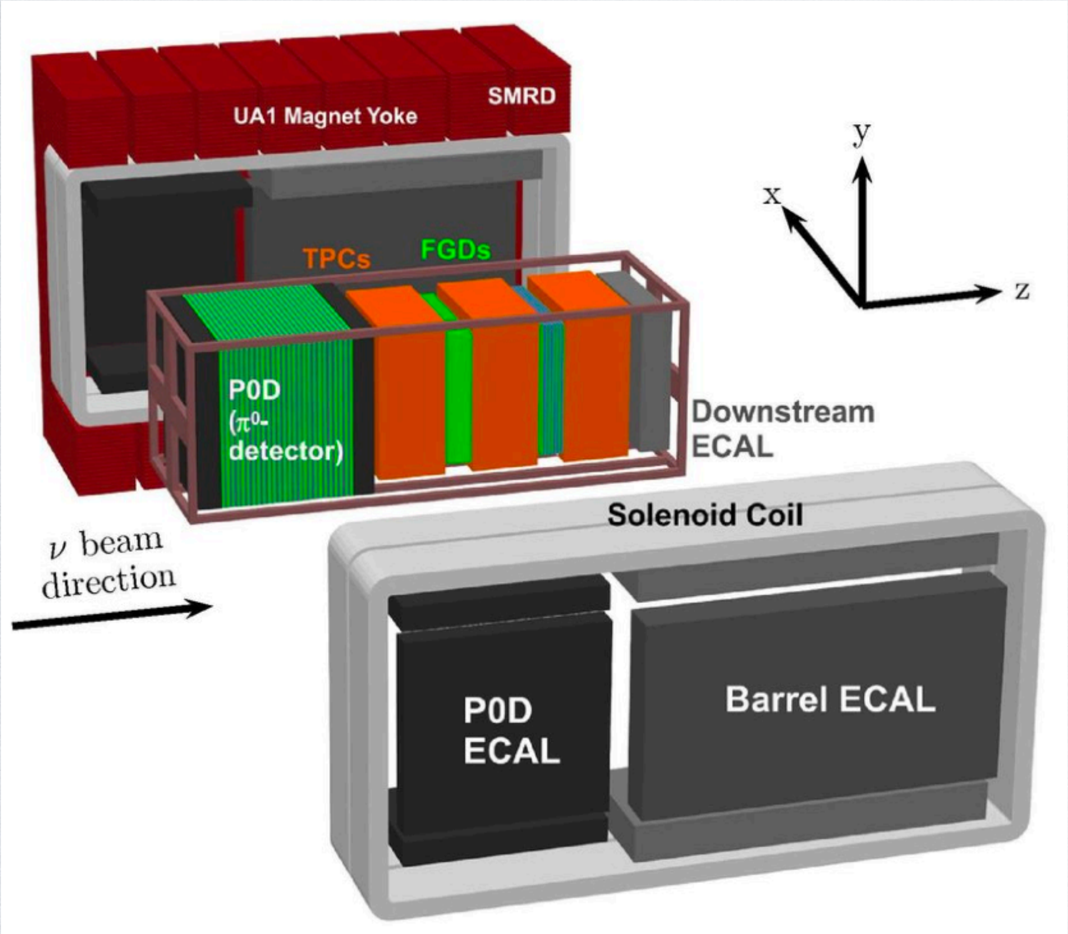
arXiv:2203.08022

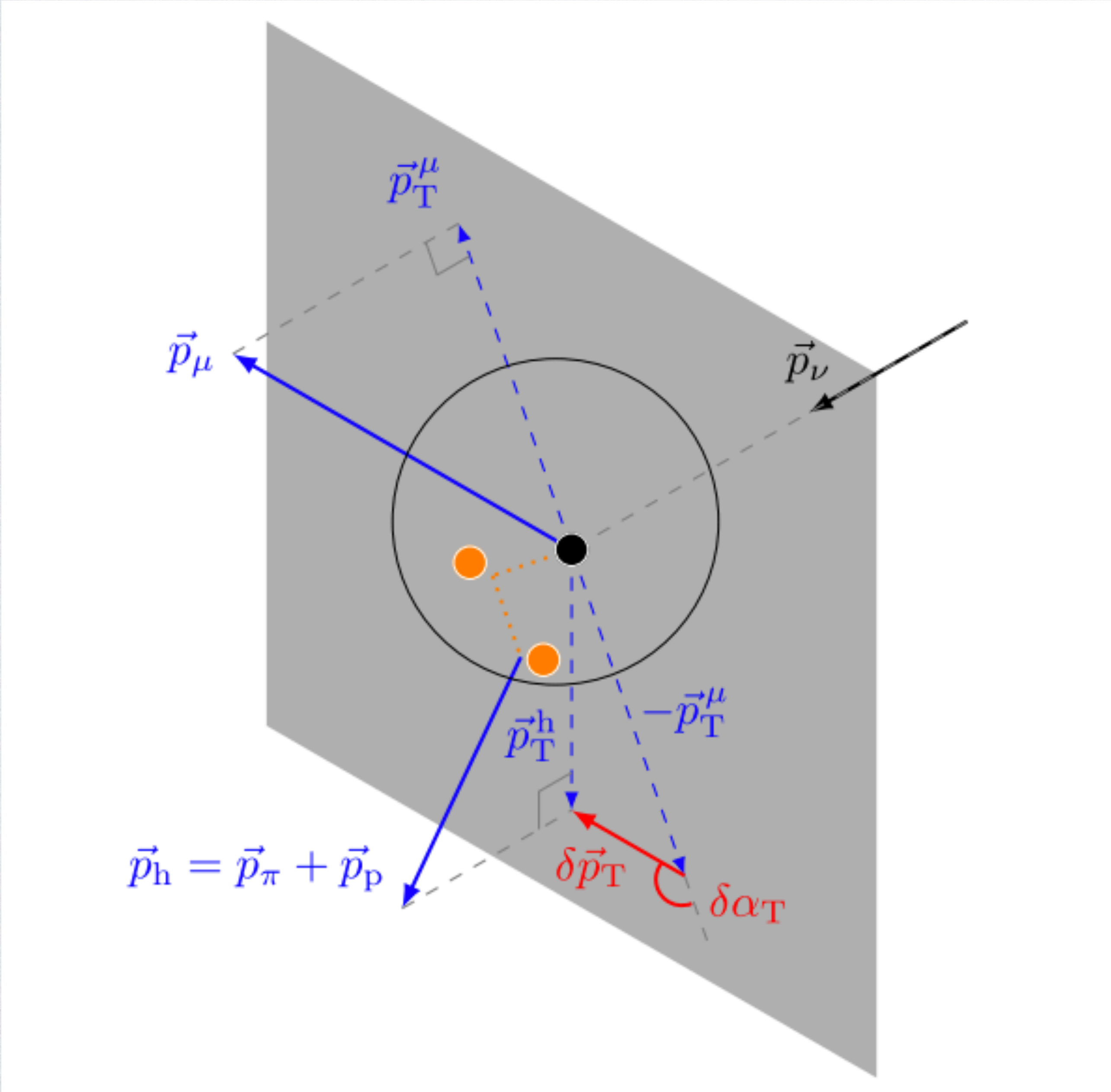
0PI: MINERVA



- Three key regions:
  - **Low muon pT, high proton kinetic energy**
    - **Few events in data where simulation predicts 2p2h, resonant + pion absorption**
  - **Proton kinetic energy near 0.2 GeV**
    - **Low Pt: relatively good agreement with MINERvA 2p2h tune**
    - **High Pt: Tune not sufficient at high Pt**
  - **High Pt, low Tp:**
    - **Poor agreement in a region dominated by Quasi-Elastic + FSI**

1PI:T2K

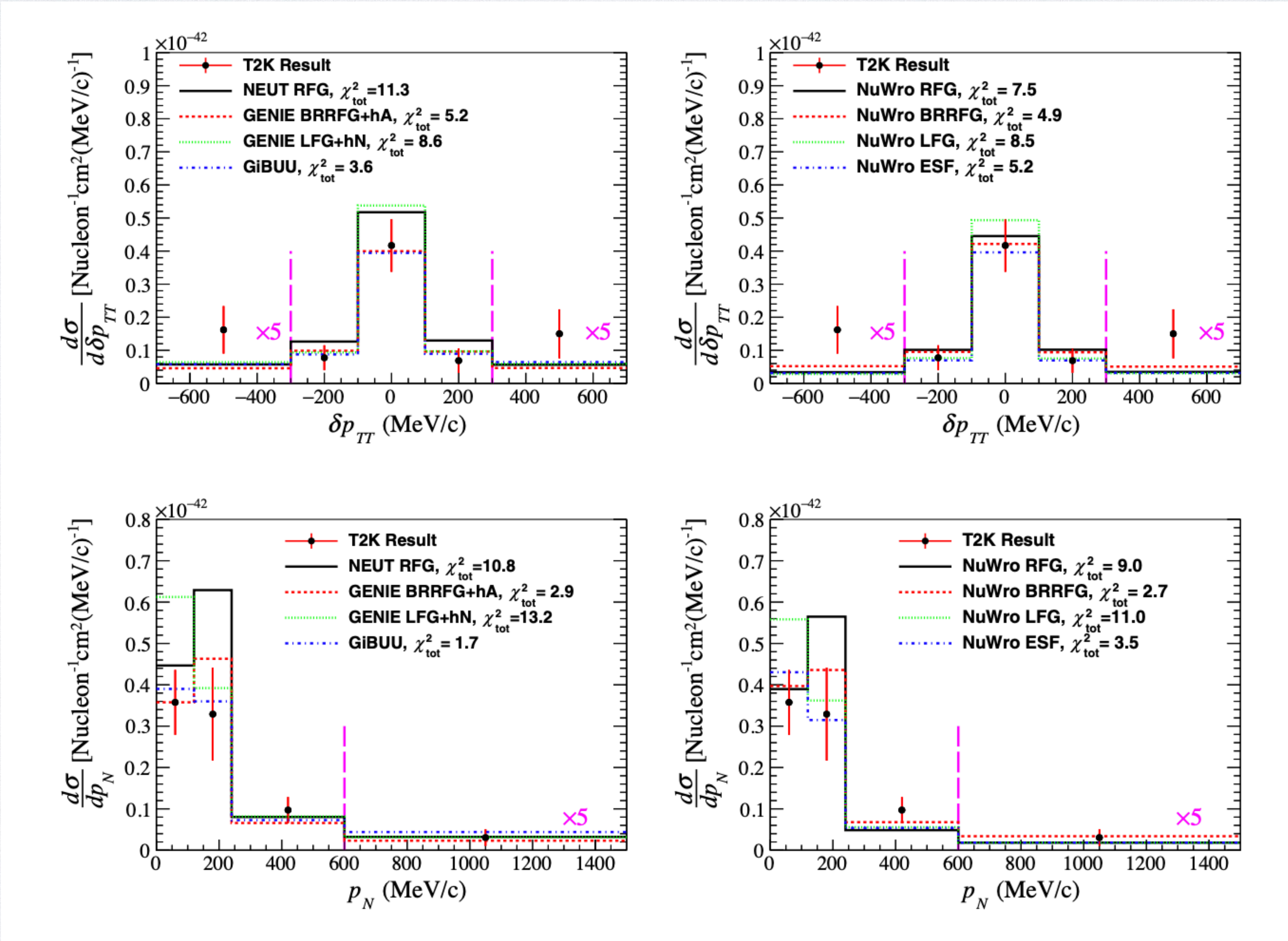




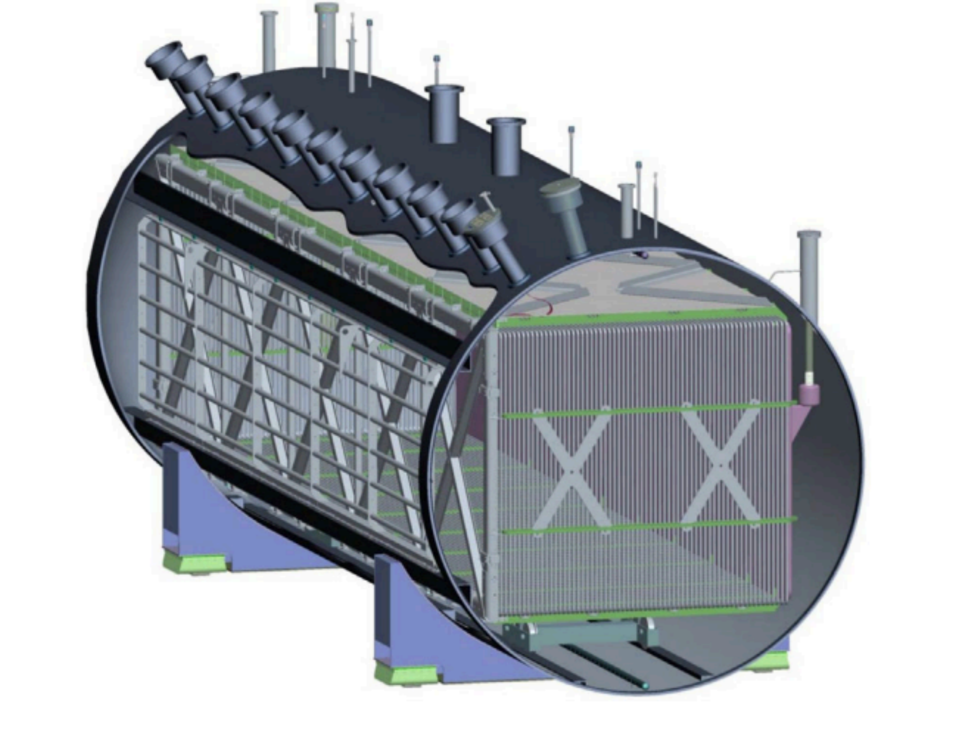
(b) $\delta\vec{p}_T$ and $\delta\alpha_T$.

PHYSICAL REVIEW D 103, 112009 (2021)

$$\nu_\mu + \mathrm{A} \rightarrow \mu^- + \pi^+ + \mathrm{p} + \mathrm{A}',$$



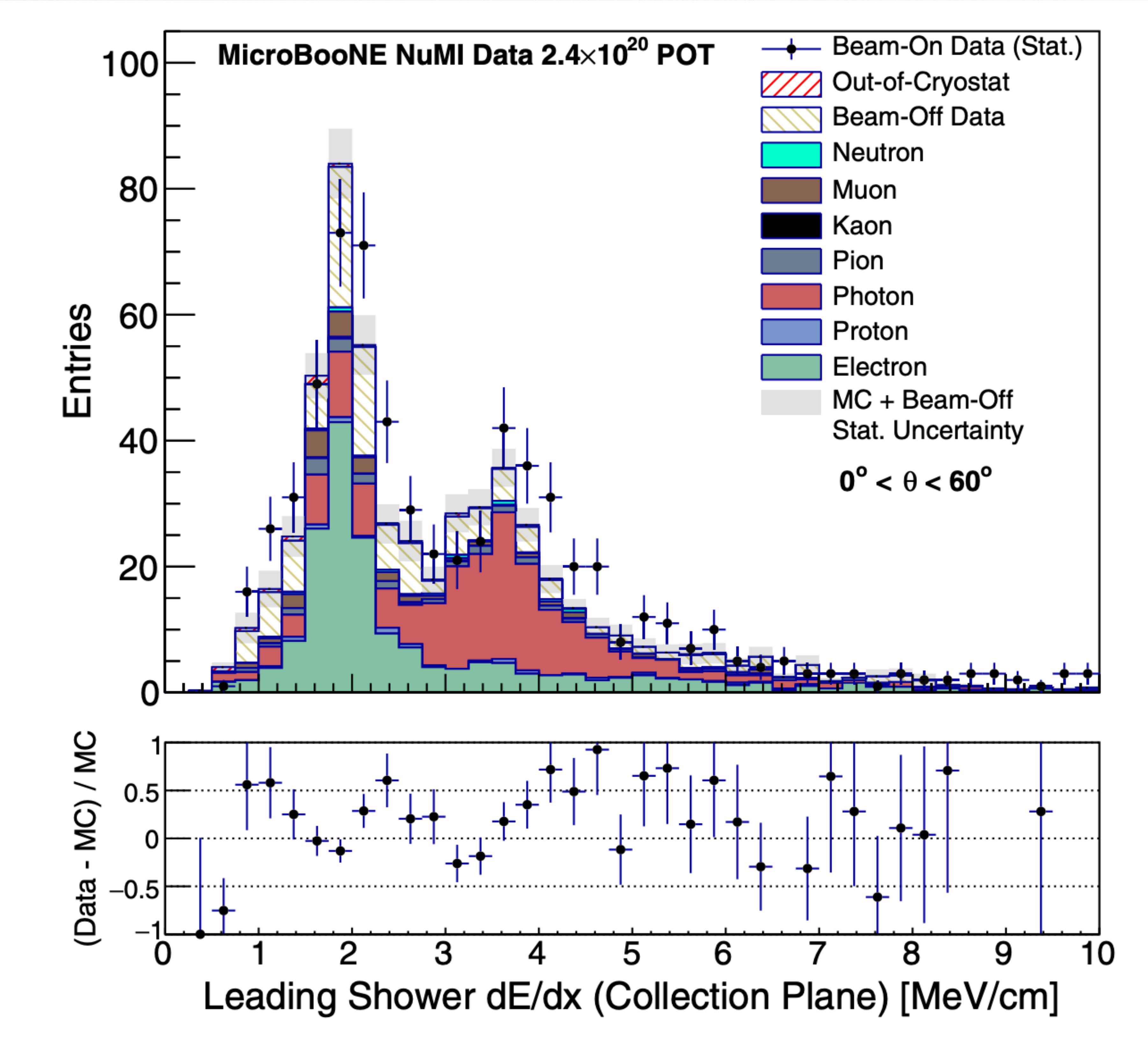
- **T2K ν_μ 1piNp**
- **Some preference for GiBUU** over other models
- **Poor agreement in p_n for Fermi gas models** (LFG/RFG)
- Statistically limited

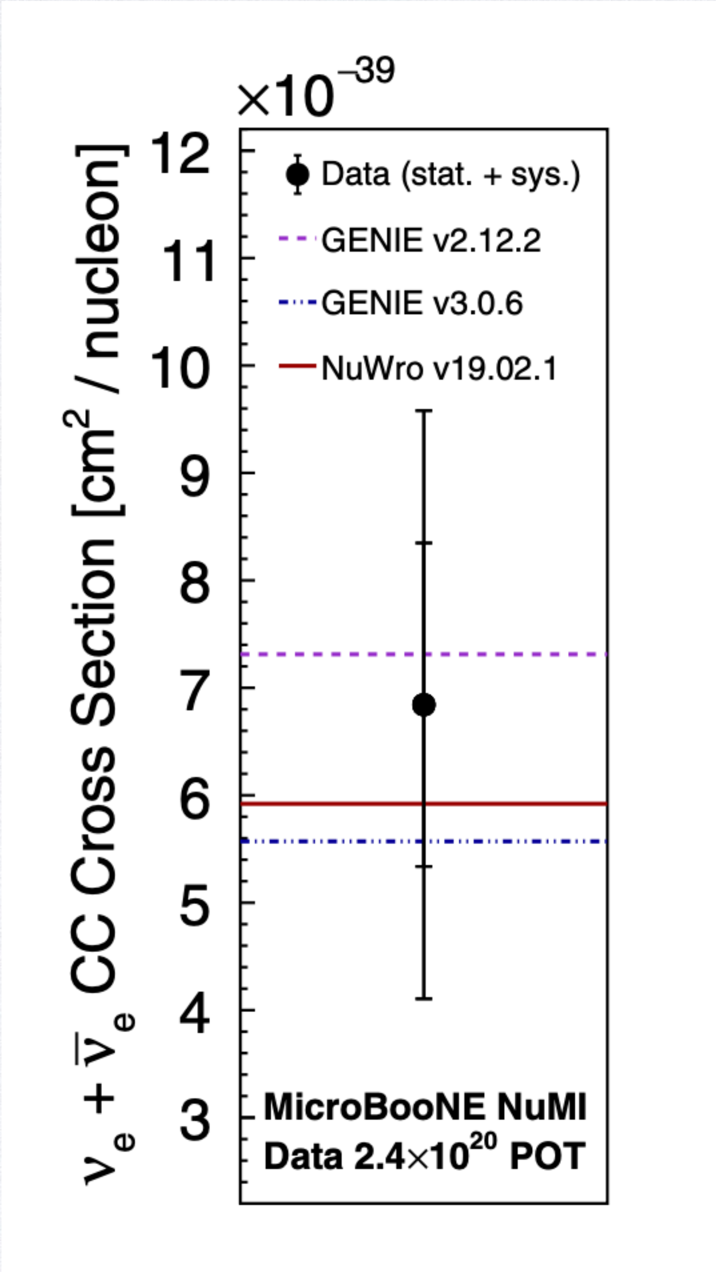


INCLUSIVE: MICROBOONE

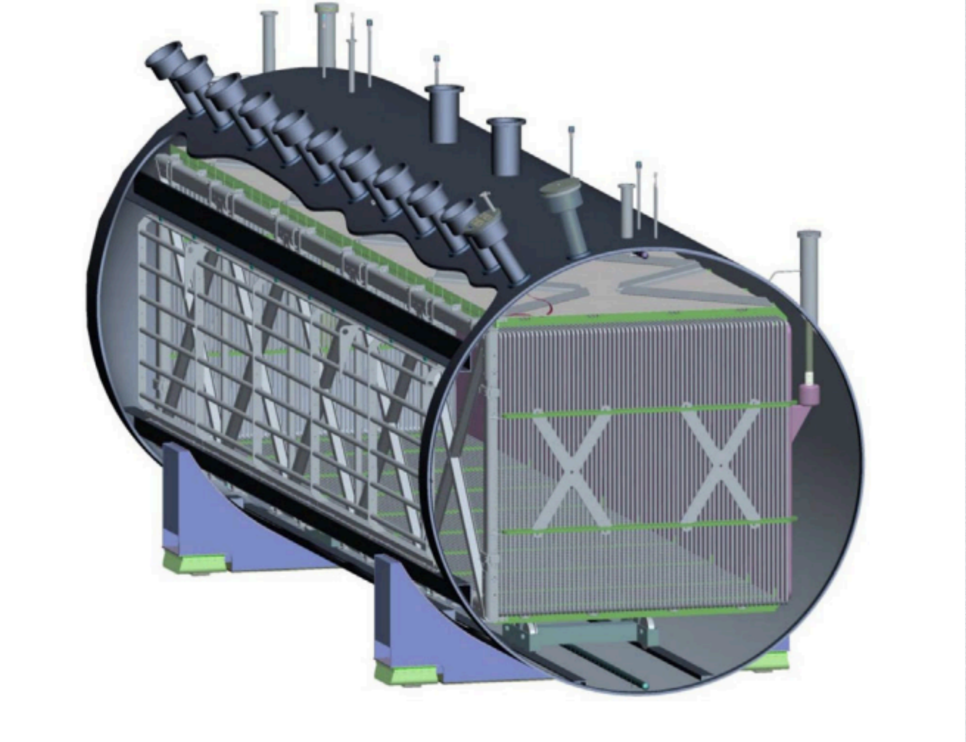
Inclusive

Phys. Rev. D 104, 052002





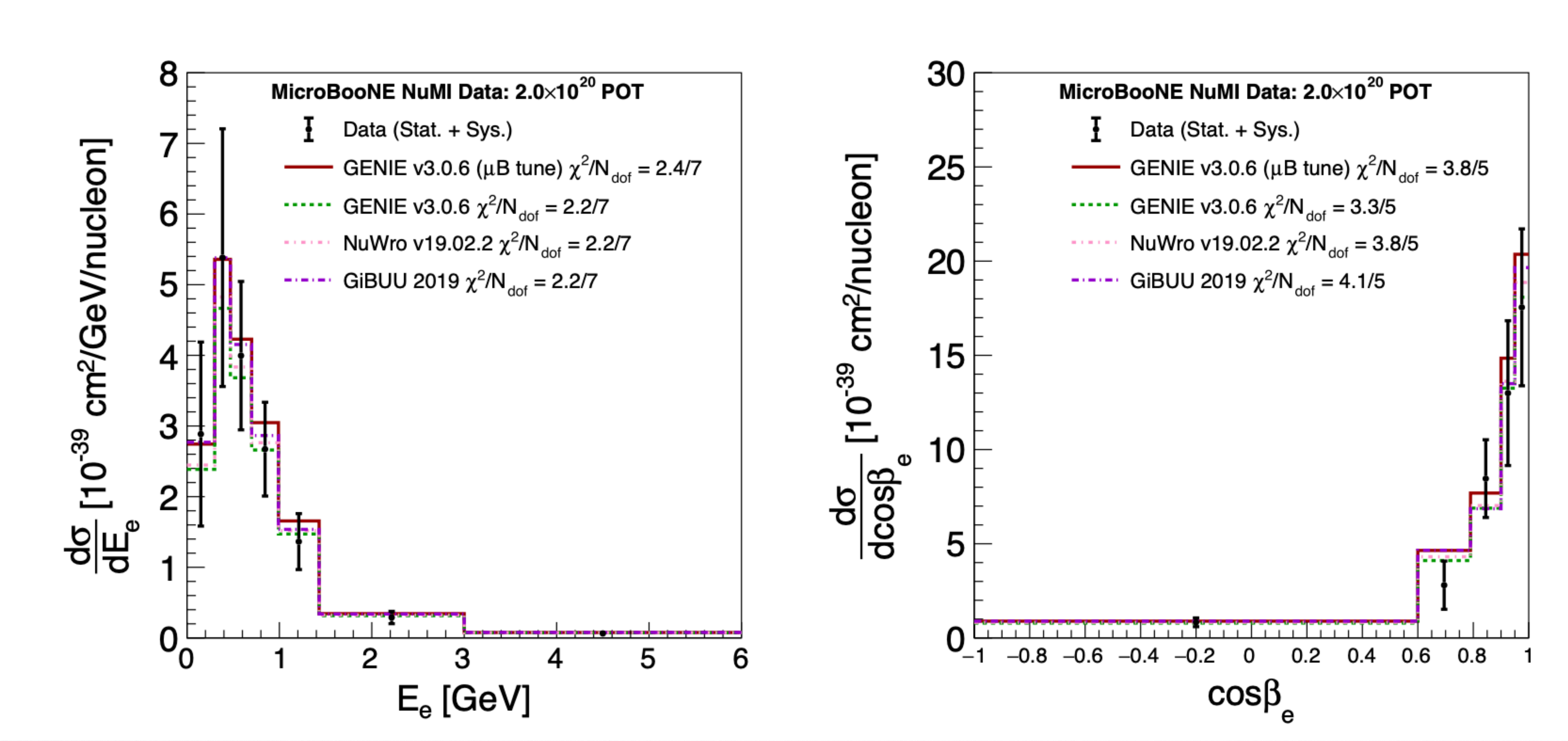
- **MicroBooNE inclusive $\nu_e+\bar{\nu}_e$ CC** cross section on Ar
- **Agreement with models** within large uncertainties
- First measurement using **off-axis NuMI beam**
- **Demonstration of electron/photon separation** in LAr detectors



INCLUSIVE: MICROBOONE

Inclusive

Phys. Rev. D **105**, L051102



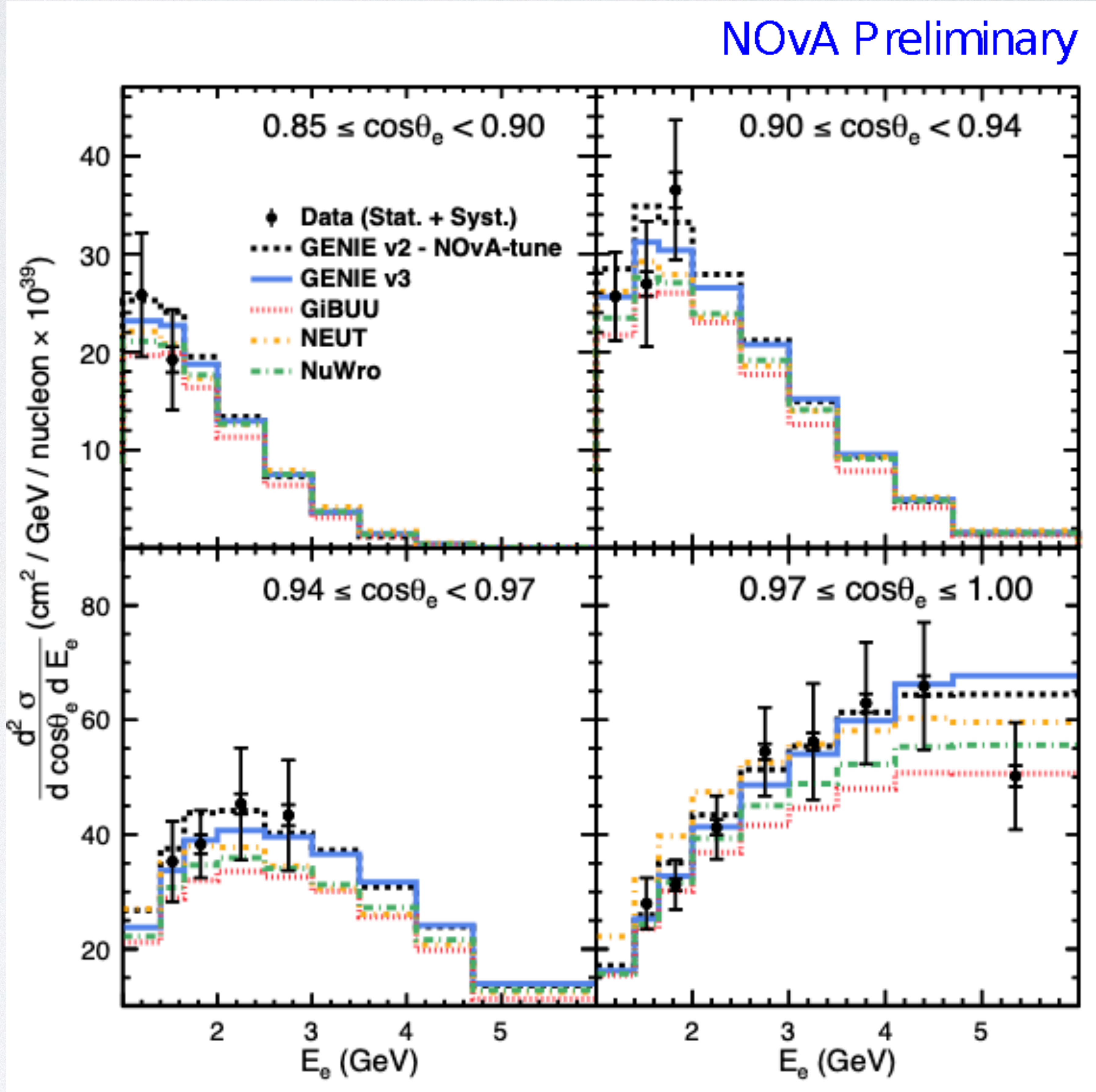
- Expanded into a **differential cross section versus electron energy and angle**
- Compared to GENIE, NuWro, GiBUU
  - **Agrees within large uncertainties** (statistically dominated)

INCLUSIVE: NOVA

Inclusive

- NOvA ν_e **CC interactions** → ~9,200 signal events
  - Largest inclusive ν_e sample to date at this energy scale
- Cross section reported at 17 kinematic points in (E_e,cos θ_e)
- **15 - 20% uncertainty**
  - Typically **dominated by flux and nu-A interaction** model systematics

χ^2 (17 d.o.f.)	Generator
24.1	GENIE v2.12.2 NOvA Tune
24.3	GENIE v2.12.2
27.4	GENIE v3.00.06 (N18_10j_02_11a)
17.5	GiBUU 2019
25.1	NEUT 5.4.0
18.7	NuWro 2019

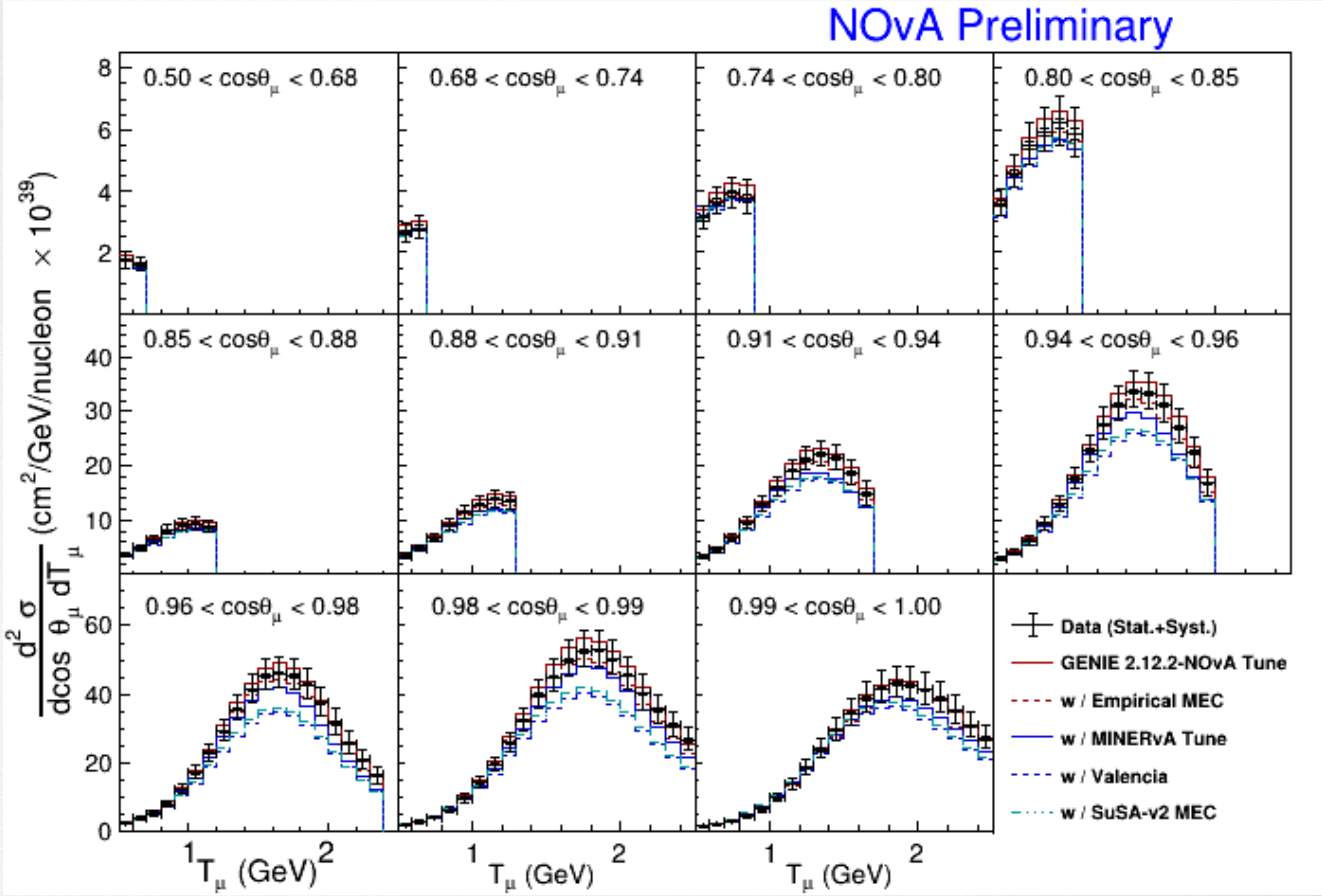


INCLUSIVE: NOVA

Inclusive

- **NOvA ν_μ cross section at low hadronic recoil**
  - T_p^{max} = 250 MeV
  - T_π^{max} = 175 MeV

12-15% uncertainty typically
→ dominated by flux systematic

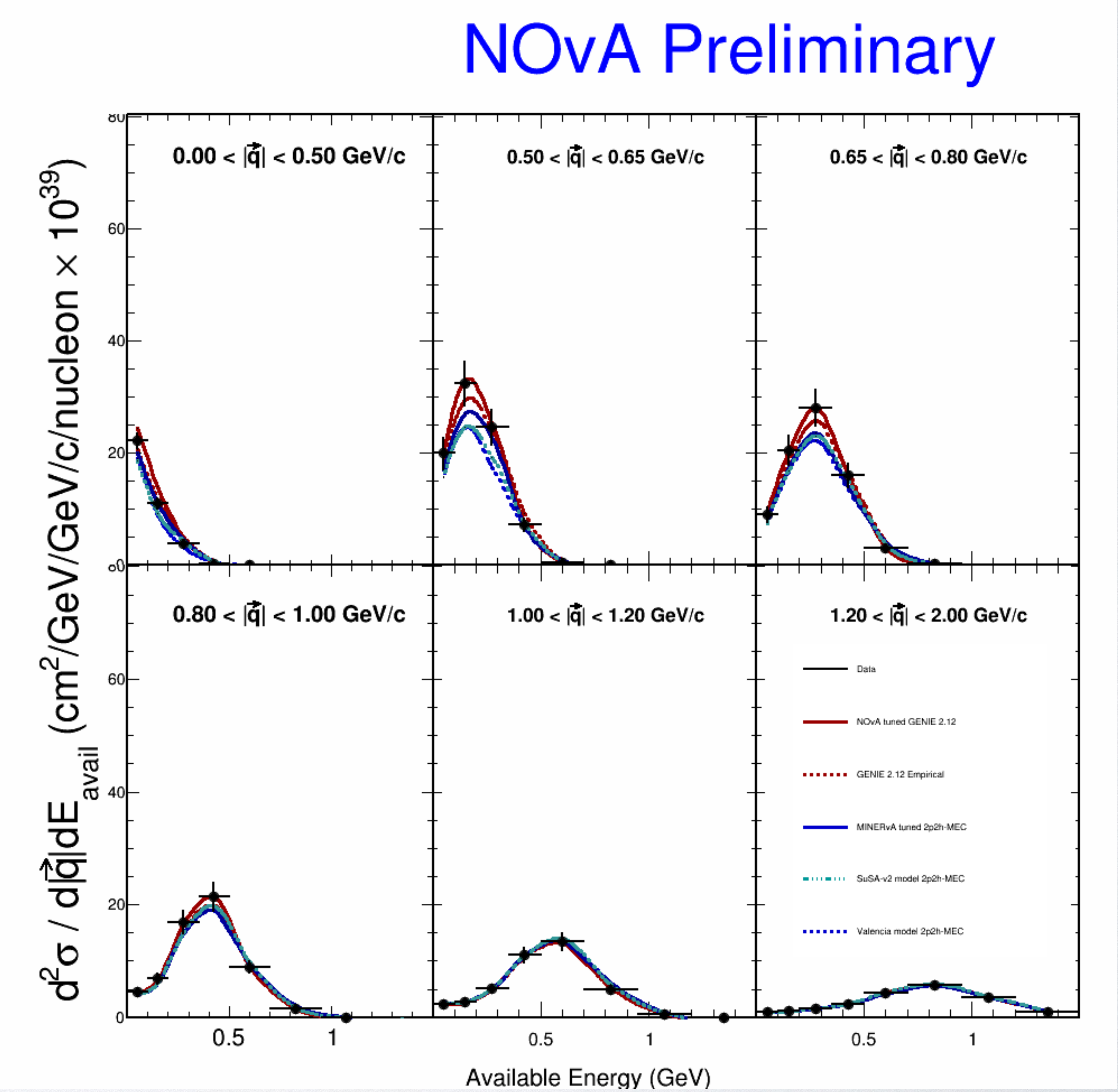


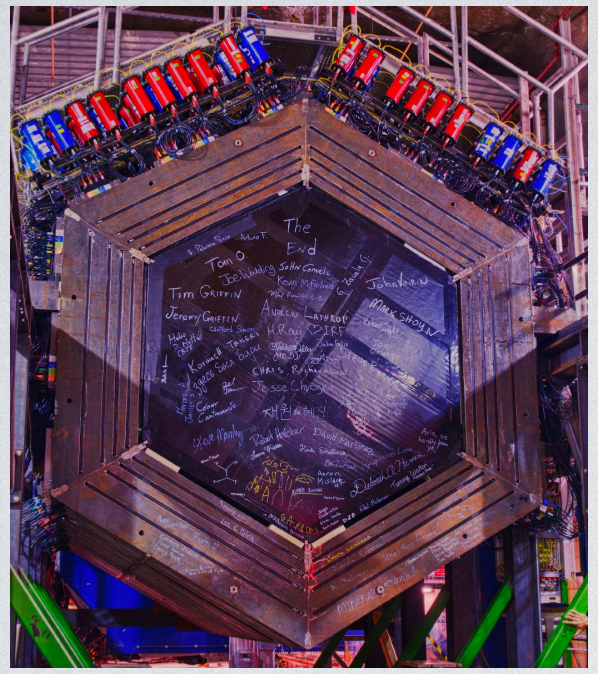
2p2h Model	χ^2 (115 d.o.f.)
GENIE v2-12.2 NOvA Tune	200
Empirical MEC	190
Valencia w/ MINERvA Tune	340
Valencia	630
SuSA - v2	620

INCLUSIVE: NOVA

Inclusive

- **NOvA's first ν_μ measurement in |q| and E_{avail}**
- 2p2h concentrated at low values of |q| and available energy
- ~**12% uncertainty** typically
  - dominated by flux systematic

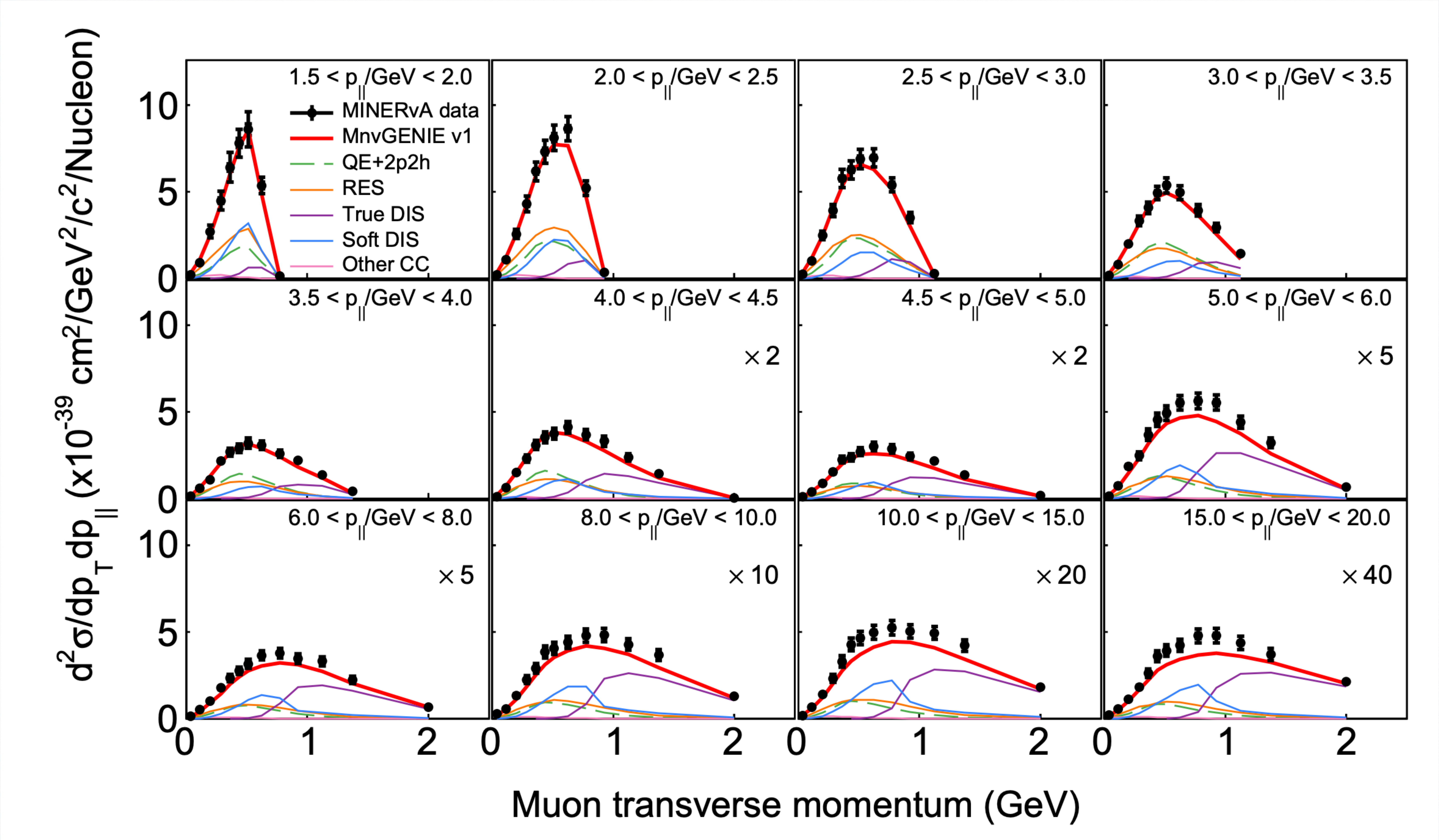




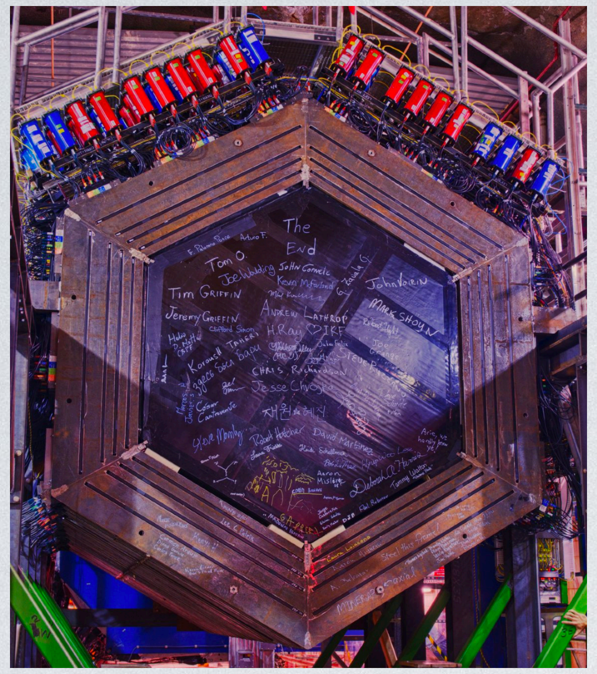
MINERVA: INCLUSIVE

Inclusive

Phys. Rev. D 101, 11 (2020)



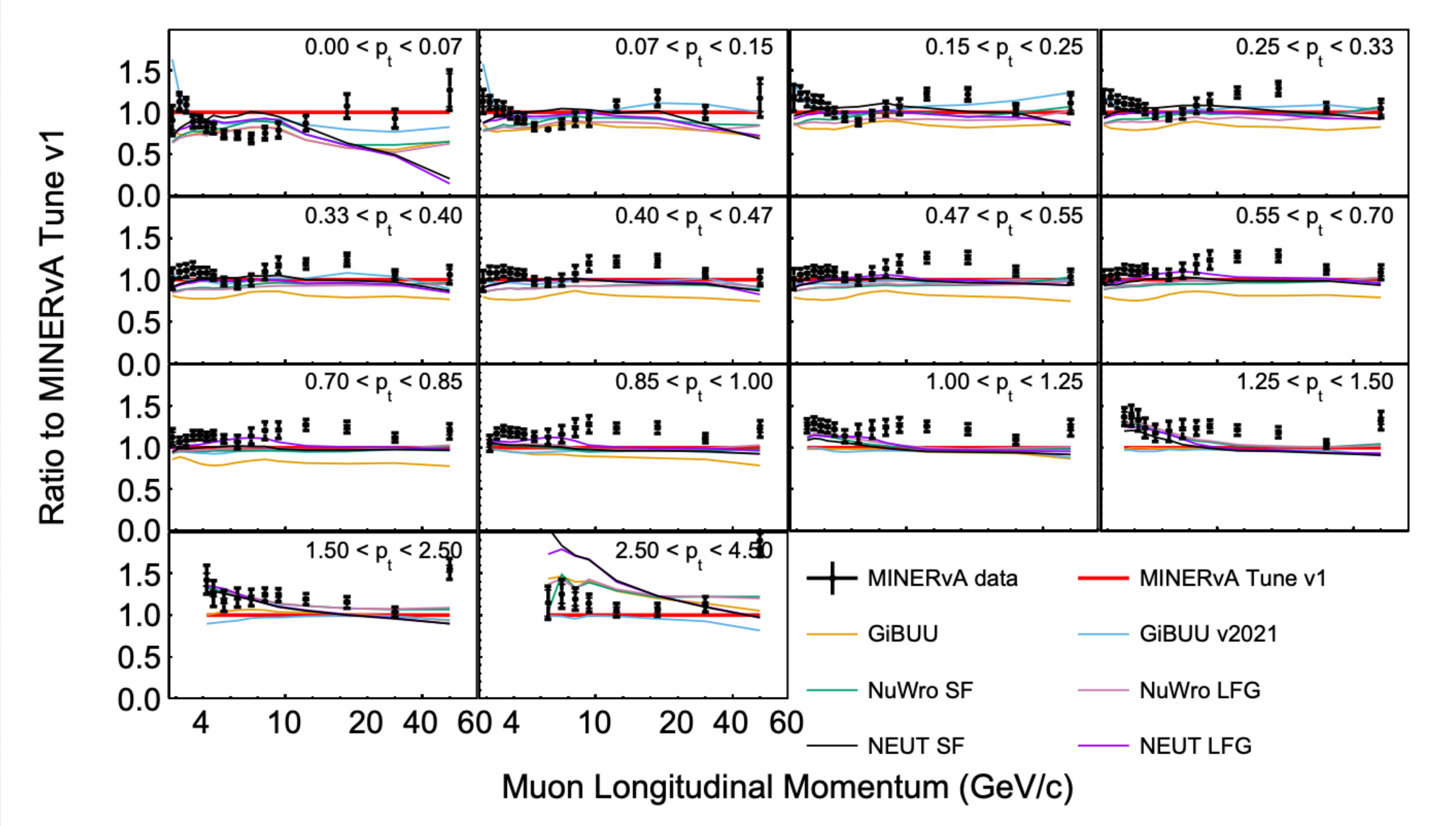
- **MINERvA ν_μ CC inclusive** cross section
  - muon longitudinal and transverse momentum
- Illustrates that MINERvA is able to **cover the full QE+RES+DIS range**
- But currently, our **only way of assessing DIS/SIS region**



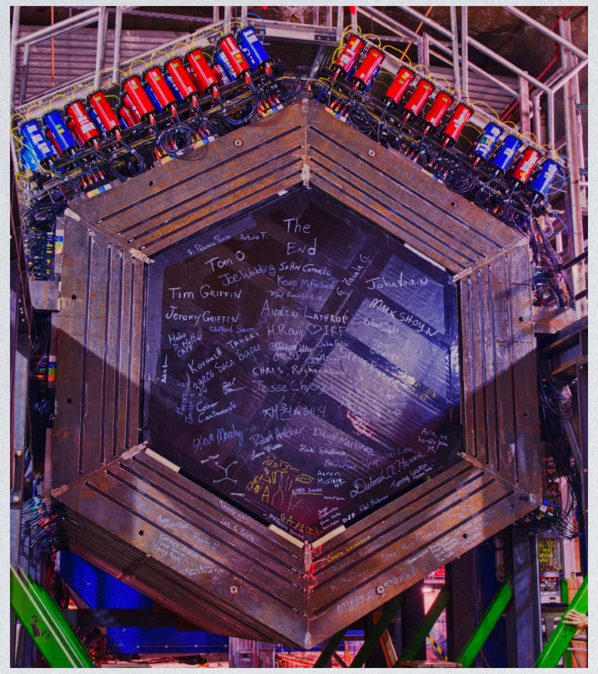
MINERVA: INCLUSIVE

Phys. Rev. D 101, 11 (2020)

Inclusive

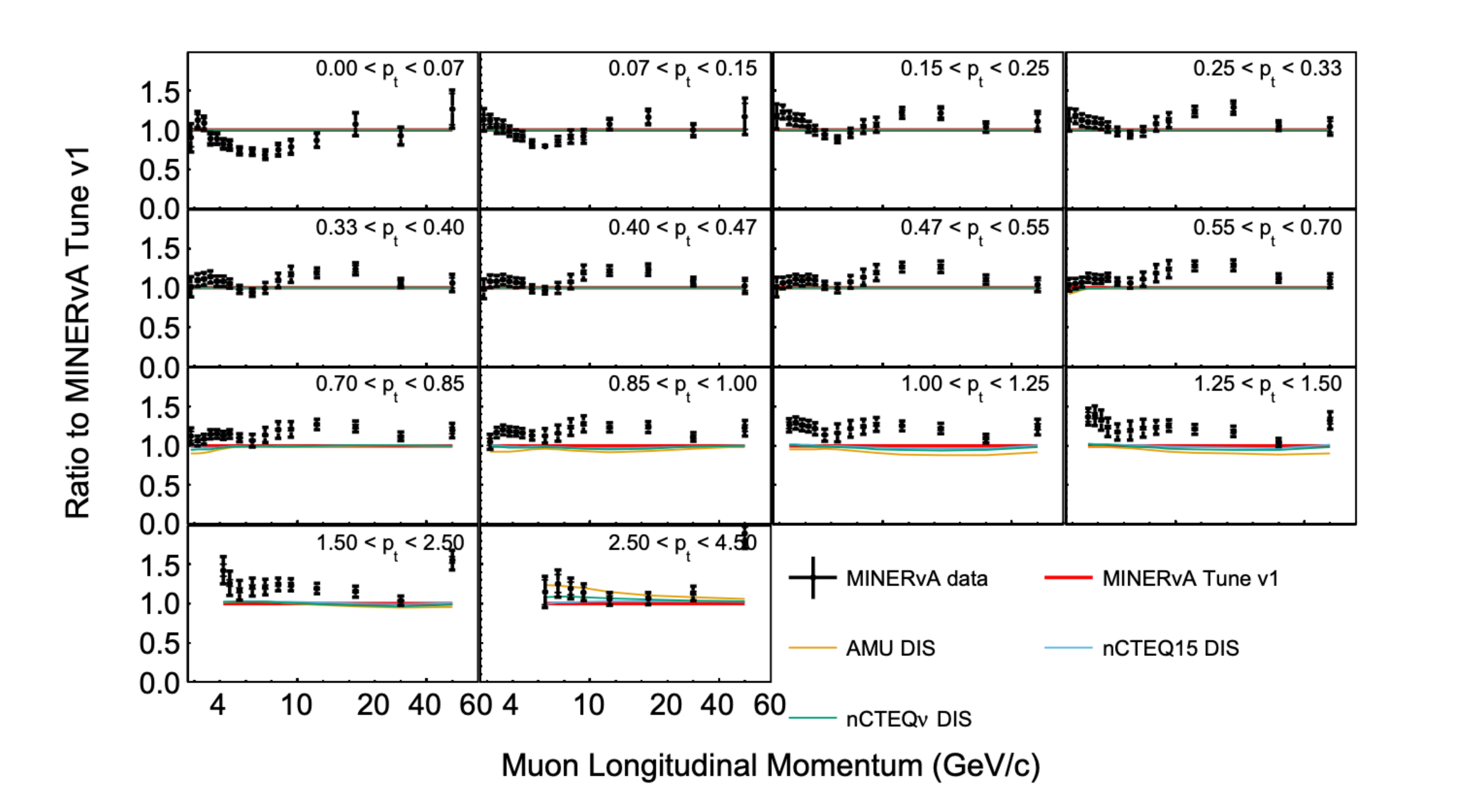


- **No models agree** well with data across all regions of phase space
  - Or even most regions of phase space
- **Best model agreement** (based on chi-square) is with **NuWro LFG**



MINERVA: INCLUSIVE

Phys. Rev. D 101, 11 (2020)



- Also compared to **several available DIS** models
- **Spread of models small compared to discrepancy with data**

WHAT'S NEXT

- Neutrino-electron scattering will **reduce flux uncertainties**
- **Testbeam measurements** will reduce detector systematics
- **Big focus on ratios** (e.g. $\nu/\bar{\nu}_{\mu}$, ν_e/ν_{μ})
- Improved reconstruction -> **exclusive measurements**

- New **Wagasci/Babymind** detectors
- **ND280 upgrade** will bring larger angular acceptance, lower tracking threshold, neutron sensitivity
- Improved **statistics**

- **Multi-differential** cross sections
- Doubled **statistics**, better **reconstruction**
- **Special variables** (e.g. TKI)

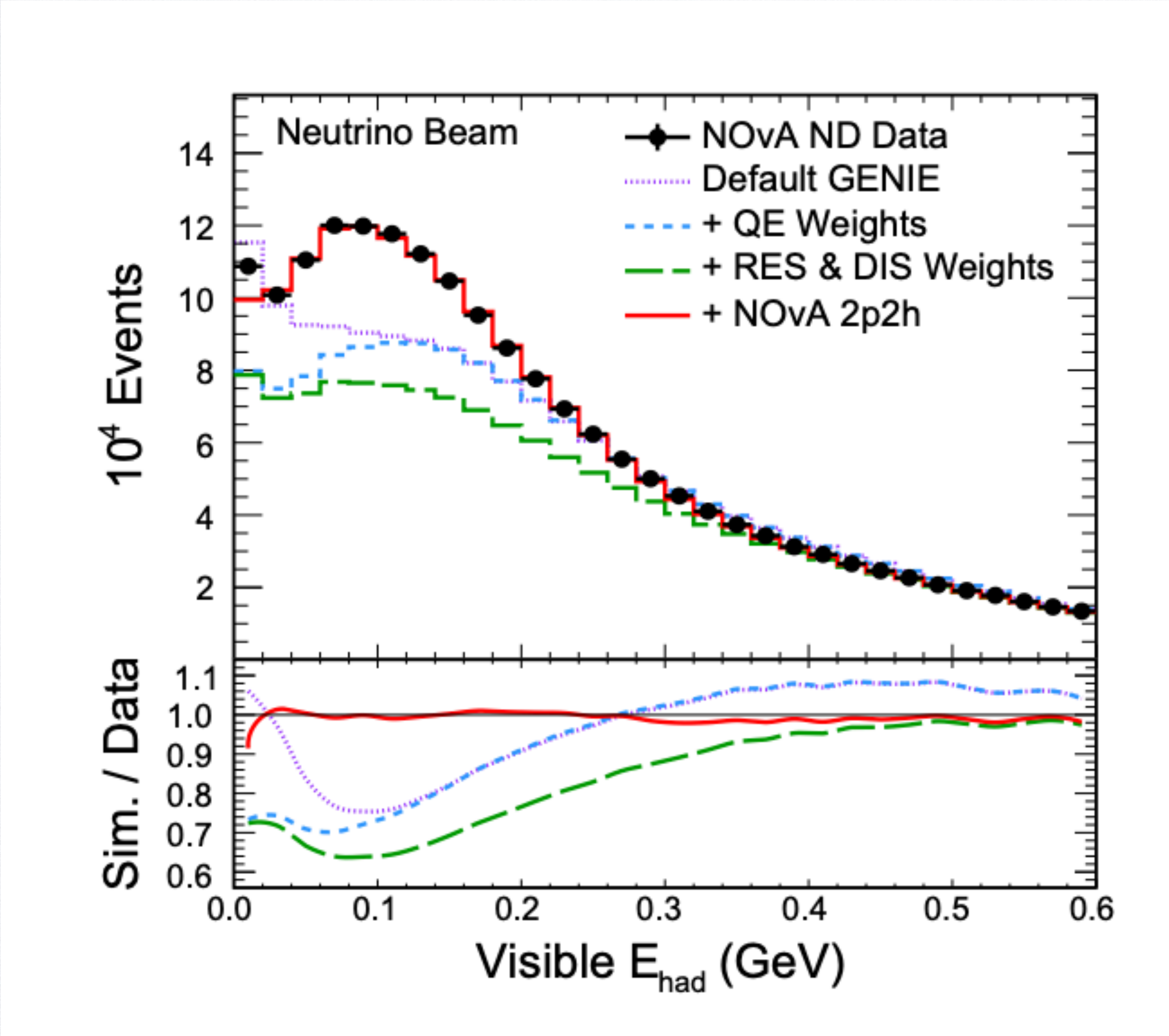
- Completed data taking in 2019, but **30+ active analyses ongoing**
- **A-dependence** of 0-pi, 1-pi
- **Deep and shallow inelastic** scattering
- Data preservation project

USING THIS DATA

- We are **collecting and publishing** lots of data, but that's really just **half the battle**. We need to **use the data**. There has been some progress here:

Experiments are developing their own tunes

Example from NOvA



Eur.Phys.J.C 80 (2020) 12, 1119

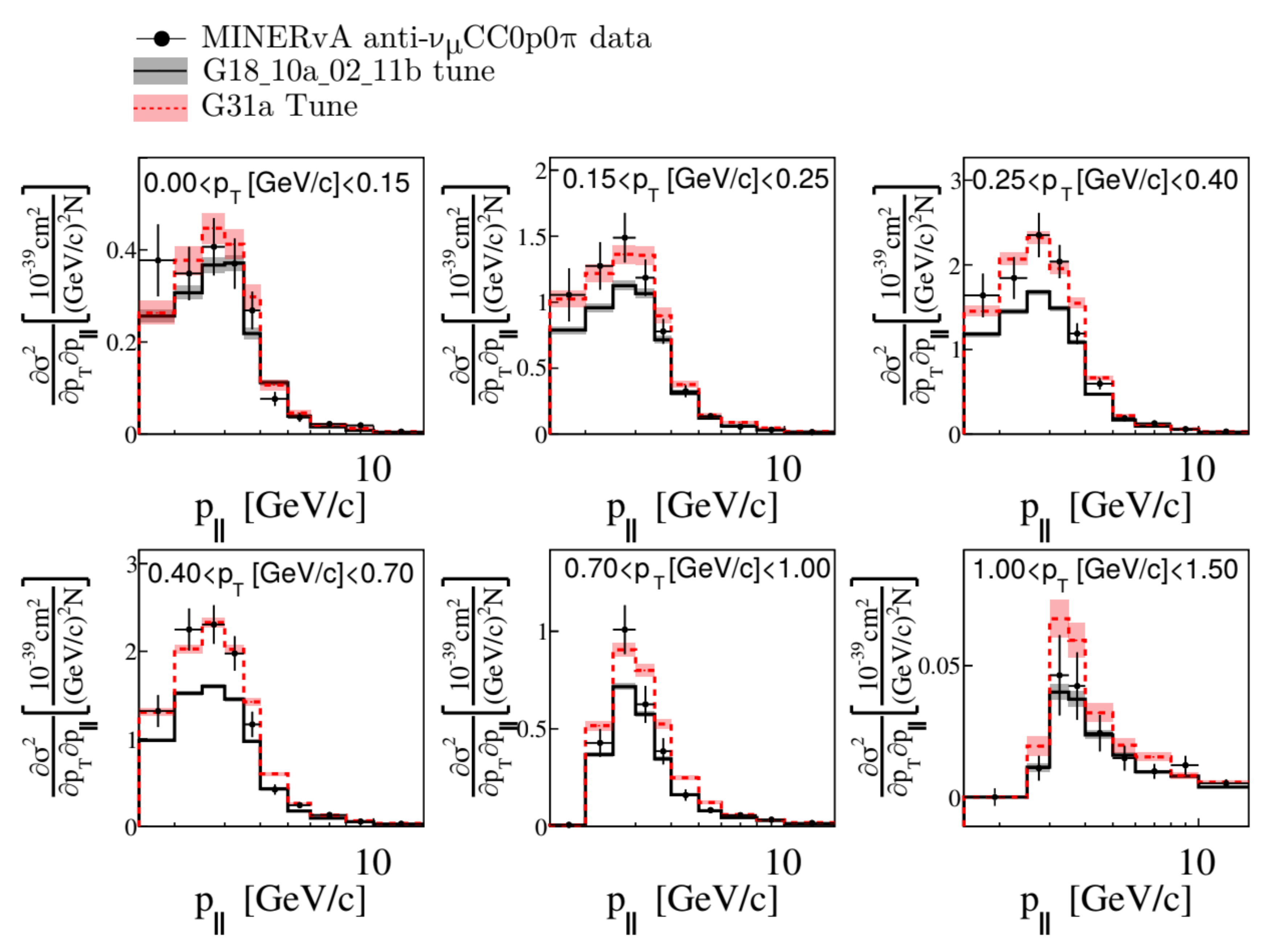


FIG. 27: Comparison of the G18_10a_02_11b and G31a tunes against MINERvA $\bar{\nu}_\mu$ CC0p0π double differential data [17]. The comparisons are restricted to the $0 < p_T < 1.5$ GeV/c phase space. The predictions are computed using the parameters specified in Tab. VI. The total χ^2 associated to this dataset before (after) the tune reported in Tab. VII.

GENIE Collaboration, Paper in Preparation

GENIE is executing a long-term plan aimed at an eventual global tune

Example **fit to MINERvA** data

MORE AT NEUTRINO 2022

- Lots more detail in posters

205. Status of the Measurement of Neutrino-Electron Elastic Scattering in the NOvA Near Detector
457. Measurement of $\nu\mu$ CC Inclusive Differential Cross Section and Estimation of 2p2h-MEC Contribution using NOvA
467. A Data-driven Measurement of the Electron Antineutrino Charged-current Inclusive Cross Section with NOvA
469. Neutrino Tridents in the NOvA Near Detector
506. Status of the Triple Differential Muon Antineutrino CC Inclusive Cross-Section Analysis using Data Collected by the NOvA Near Detector
533. Muon antineutrino charged-current neutral pion production differential cross-section measurement in the NOvA near detector
536. Measurement of the muon neutrino charged-current interactions with low hadronic activity in the NOvA near detector
679. Status of the measurement of the muon neutrino charged-current cross section with zero mesons in the final state at the NOvA near detector
709. Status of the muon neutrino charged-current coherent pion production in the NOvA near detector

115. Single Positive Pion Production in Neutrino Neutral Current Interactions in T2K
165. Combined neutrino and antineutrino cross section measurement in the T2K near detector complex
491. Neutron tagging with SK-Gd for neutral current quasielastic interaction measurements with the T2K neutrino beam

309. Measurement of Nuclear Dependence in Inclusive Antineutrino Scattering with MINERvA
539. Multi-Neutron Antineutrino Interactions at low Available Energy in MINERvA

32. Analysis of flux-integrated semi-exclusive cross sections for charged current and neutral-current quasi-elastic neutrino scattering off Ar at energies available at the MicroBooNE experiment
56. Measuring the Neutral Current Neutral Pion Cross Section on Argon in MicroBooNE
66. Progress Toward the Extraction of an Inclusive Muon Neutrino Charged Current Triple Differential Cross Section at MicroBooNE
100. First Extraction of Single Differential Cross-Sections on Ar for CC2p Event Topologies in the MicroBooNE Detector
143. First Measurement of Differential Charged Current νμ–Argon Scattering Cross Sections In Kinematic Imbalance Variables With The MicroBooNE Detector
154. $\mu 4\nu$ at MicroBooNE: Cosmic Ray Studies of μ-Argon Interactions
314. A Measurement of Neutrino Induced Charged Current Neutral Pion Production in the MicroBooNE Experiment
531. MicroBooNE Electron Neutrino Cross Section without Visible Pions
514. Neutral Current Pion Production Measurement in MicroBooNE
648. Measurement of the Λ Baryon Production Cross Section in Neutrino Interactions with MicroBooNE

- And stay tuned for more cross section talks:

Xianguo Lu
Cross sections @ future experiments

Steven Gardiner
MicroBooNE cross section results

CONCLUSION

- There is a **very active cross section analysis program** by MINERvA, MicroBooNE, NOvA, and T2K preparing for oscillation measurements of the future
- Fully exploiting the datasets we are collecting **will be challenging**
- **Many thanks** to colleagues who provided material for this talk:

THANKS FOR LISTENING

BACKUP

MOTIVATION

- Recent oscillation results reflect the importance of cross sections:
- And looking beyond 3-flavor measurements
  - An accurate understand of our beams, detectors, interactions will be critical to proving to ourselves and the world that we have found New Physics (if we do!)
  - Neutrinos interact very rarely — what happens when they do is interesting physics on its own!

T2K

Phys. Rev. D 103, L011101
(3-flavor ν_μ $\bar{\nu}_\mu$)

Error source	1Rμ ν-mode	1Rμ $\bar{\nu}$-mode
Flux (constr. by ND280)	4.3%	4.1%
Xsec (constr. by ND280)	4.7%	4.0%
Xsec (all)	5.6%	4.4%
Flux + Xsec (constr. by ND280)	3.3%	2.9%
Flux + Xsec (all)	5.4%	3.2%
SK detector effects+FSI+SI	3.3%	2.9%
Total	5.5%	4.4%

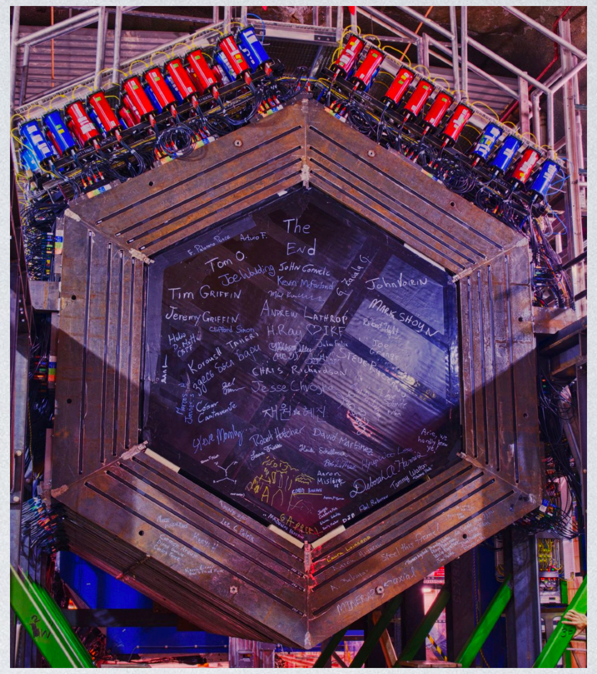
NOvA

Phys.Rev.Lett. 127 (2021) 20, 201801
(Active-Sterile Antineutrino Mixing)

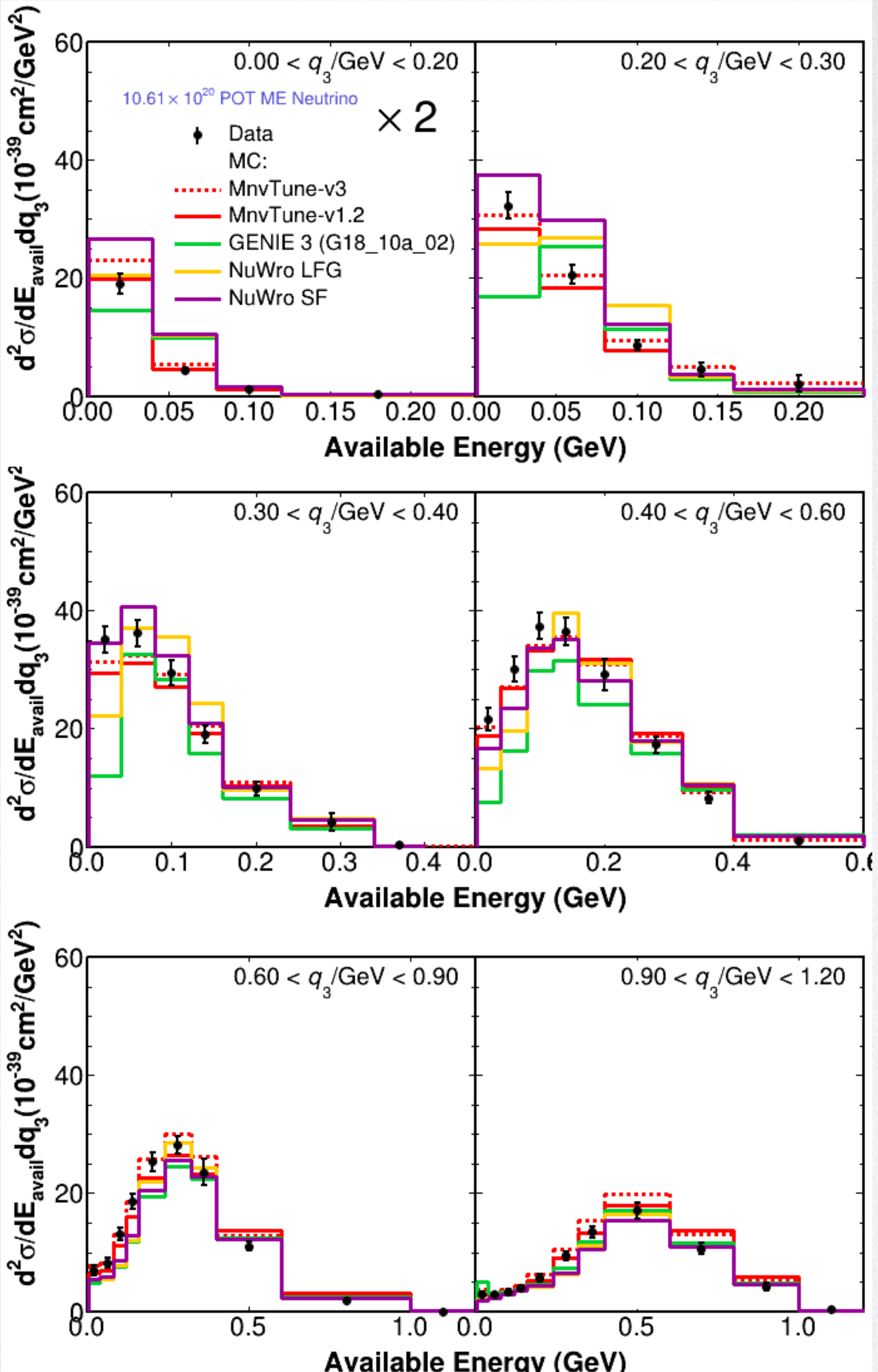
Uncertainty	NC signal difference (%)	CC background difference (%)
Calibration	13.8	9.1
Detector Response	4.9	3.8
ν Interactions	4.1	10.8
Beam	1.7	1.3
Neutron Response	0.5	0.2
Tau Cross-Section	-	7.6
Total	15.3	16.5

arXiv:2110.13372

MINERVA: INCLUSIVE



Inclusive



- **MINERvA ν_μ cross section versus q3 and available energy** separates QE, RES, 2p2h
- **MINERvA tunes agree relatively well** by design
- **GENIE and NuWro** also agree well in most regions but **struggle in QE-enriched** regions