Neutrino Cross Section Experiments

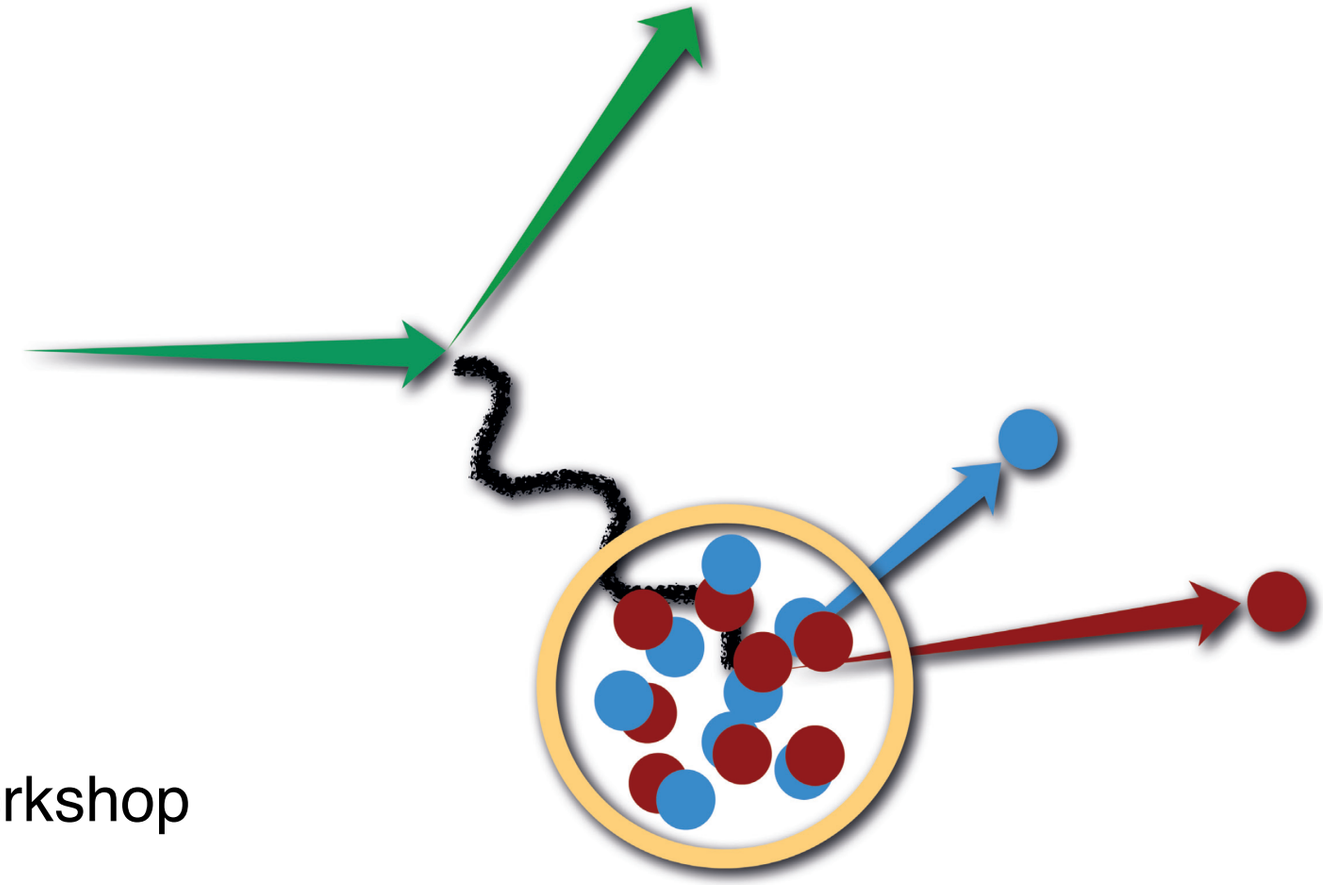


Image from the workshop series on neutrino scattering (NuInt2014)

Kendall Mahn
Michigan State University

International Neutrino Summer School
Fermilab
Aug 13th 2019

Office of Science
U.S. Department of Energy

Disclaimer

- I speak (too) fast in English… sorry…
- Please! ask me to repeat or slow down
- It is OK to raise your hand or interrupt with a question

Feedback? Comments? mahn@pa.msu.edu

Outline

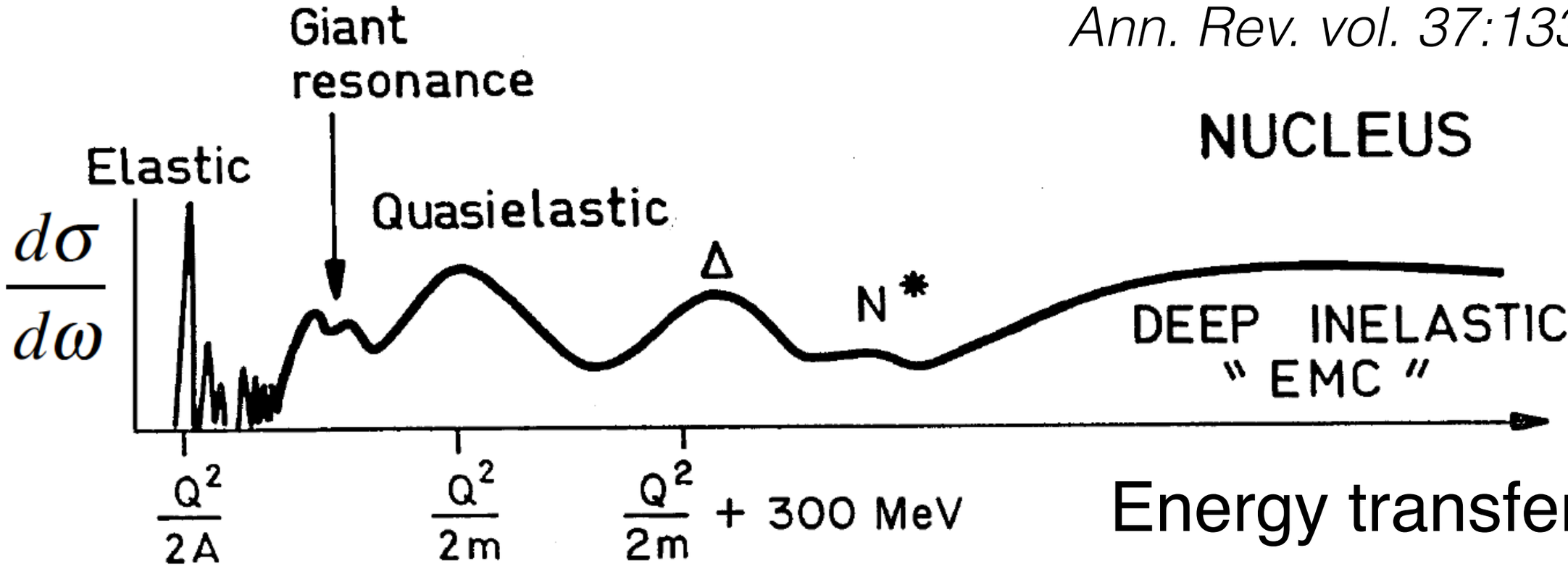
What processes are relevant to neutrino oscillation, exotic physics searches?

Recent results in neutrino cross section experiments

Future experiment ideas

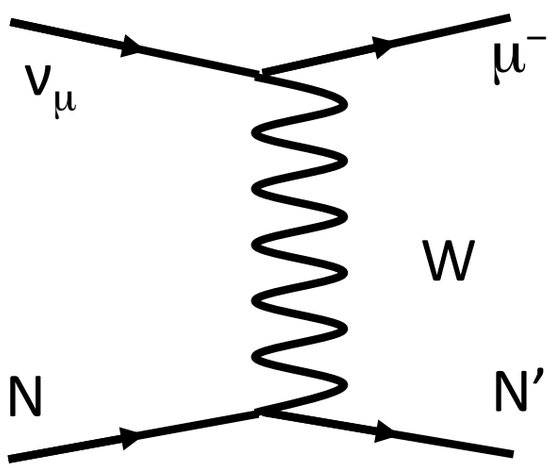
Processes in Neutrino Scattering

Ann. Rev. vol. 37:133-176



- Charged Current Quasi Elastic (CCQE) and multinucleon processes (2p2h)

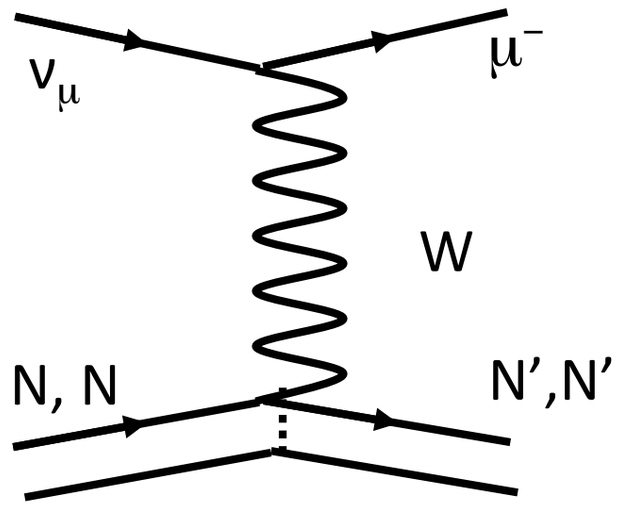
CCQE



Observable

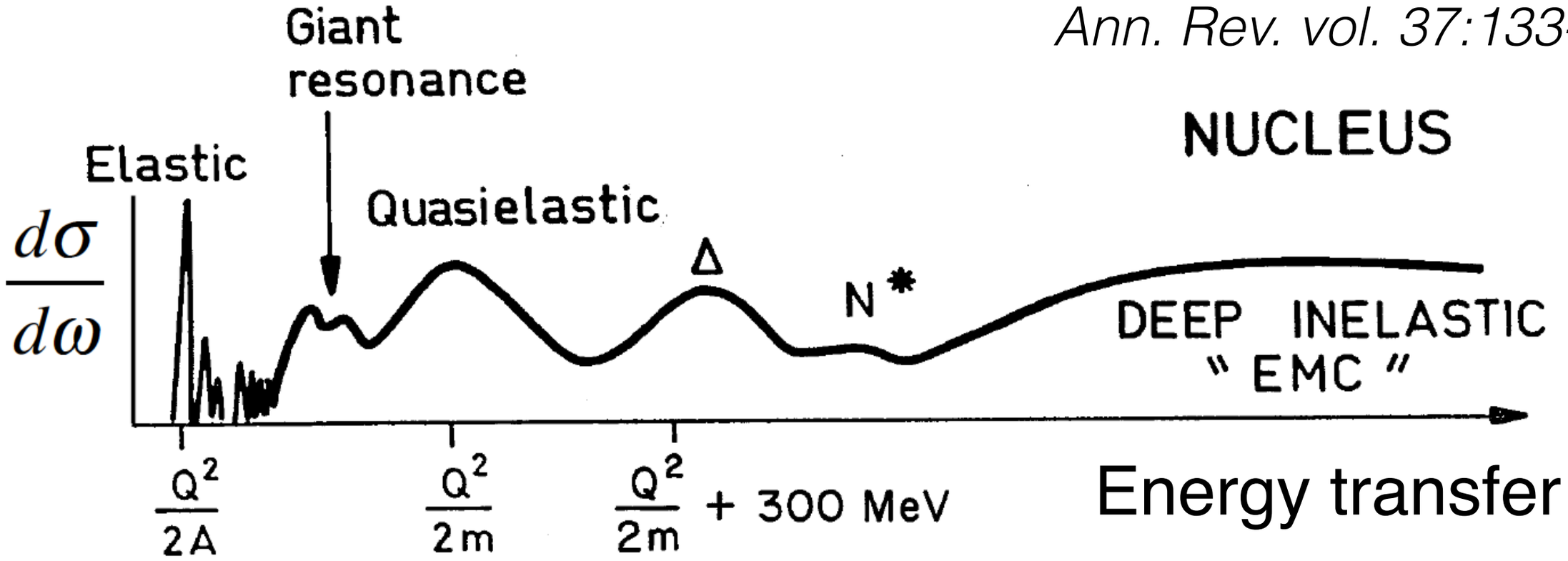
- neutrino (anti)
- muon or electron (+)
- proton (neutron)

2p2h



Processes in Neutrino Scattering

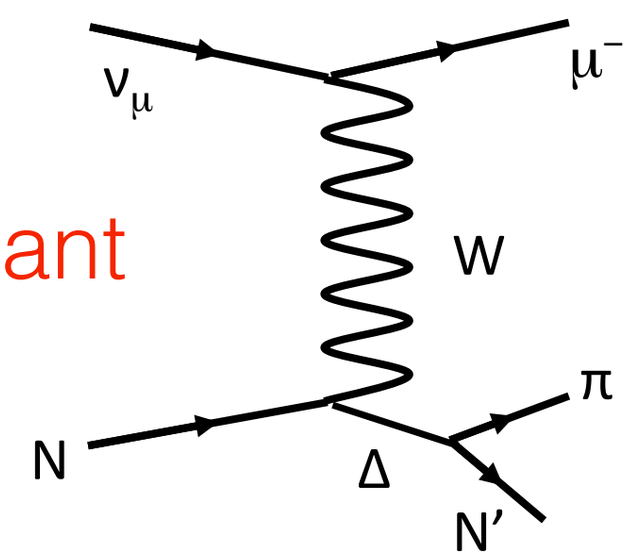
Ann. Rev. vol. 37:133-176



- Production of pions, CC1$\pi^{+/0/-}$ and NC1$\pi^{+/0/-}$

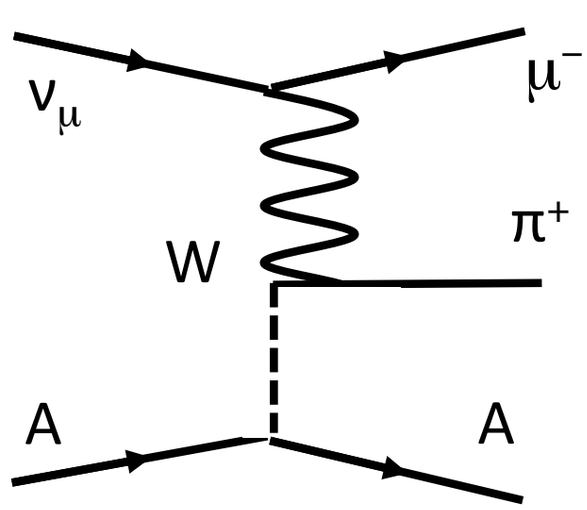
resonant

CCπ



coherent

CCπ



Processes in Neutrino Scattering

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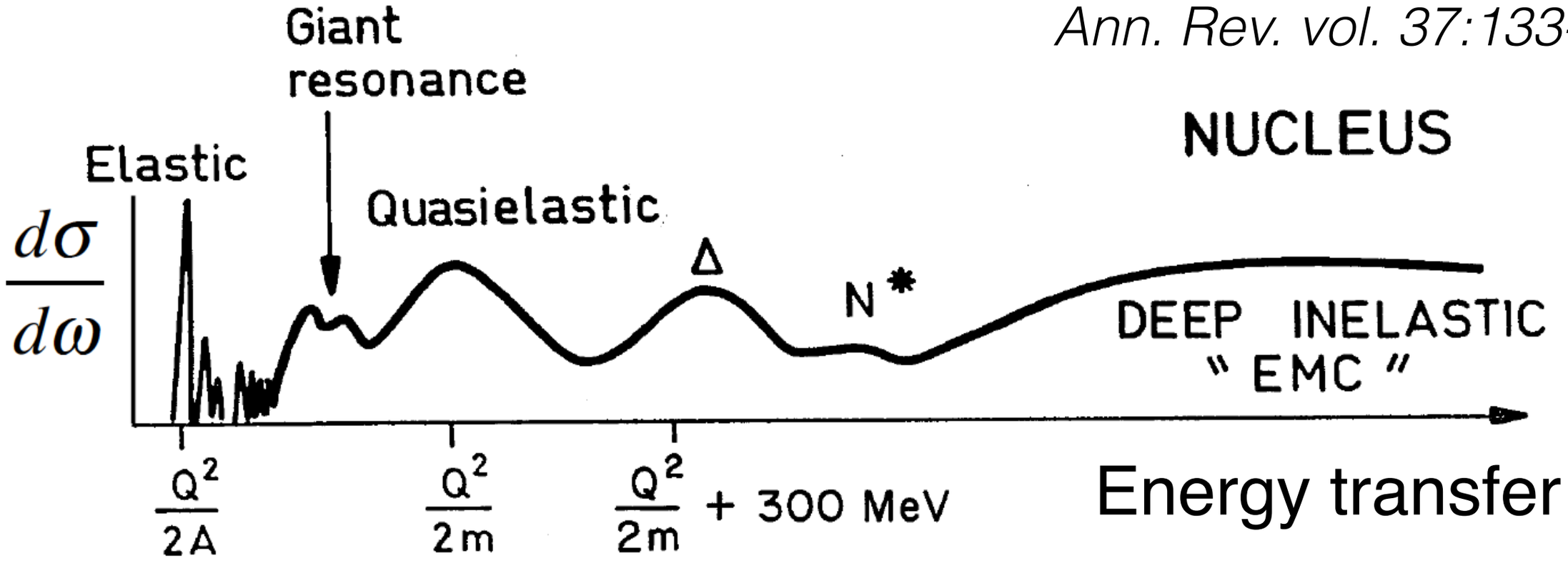

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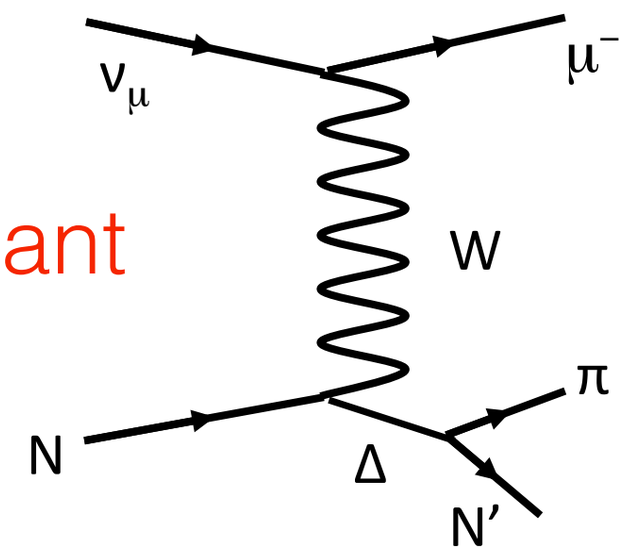
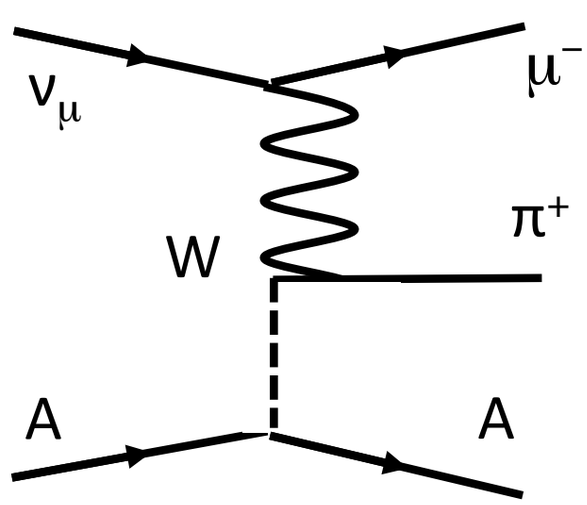


CCπ

coherent



Current:

Atmospheric: Super-Kamiokande, IceCube

Accelerator: T2K, NOvA, Short-Baseline Neutrino Program (SBN)

Future:

Accelerator/Atmospheric: Hyper-Kamiokande, Deep Underground Neutrino Experiment

US-centric program is broad.

Neutrino oscillation, exotica (e.g. sterile neutrino, dark matter searches), proton decay

Signal (or background) processes are 0.1-20 GeV charged current (CC) or neutral current (NC) neutrino or antineutrino interactions for **atmospheric and accelerator based programs**

Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}

  Is $\sin^2(\theta_{23})=0.5$? (maximal mixing?)

- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$,Δm^2_{21}

  What is the ordering of the masses ($\Delta m^2_{32/31} > 0$?)

- CP violating phase (CPV)

  Is there CPV in neutrinos?

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma^i_\beta(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Event rate used to infer oscillation physics

Oscillation analysis depends on interaction model

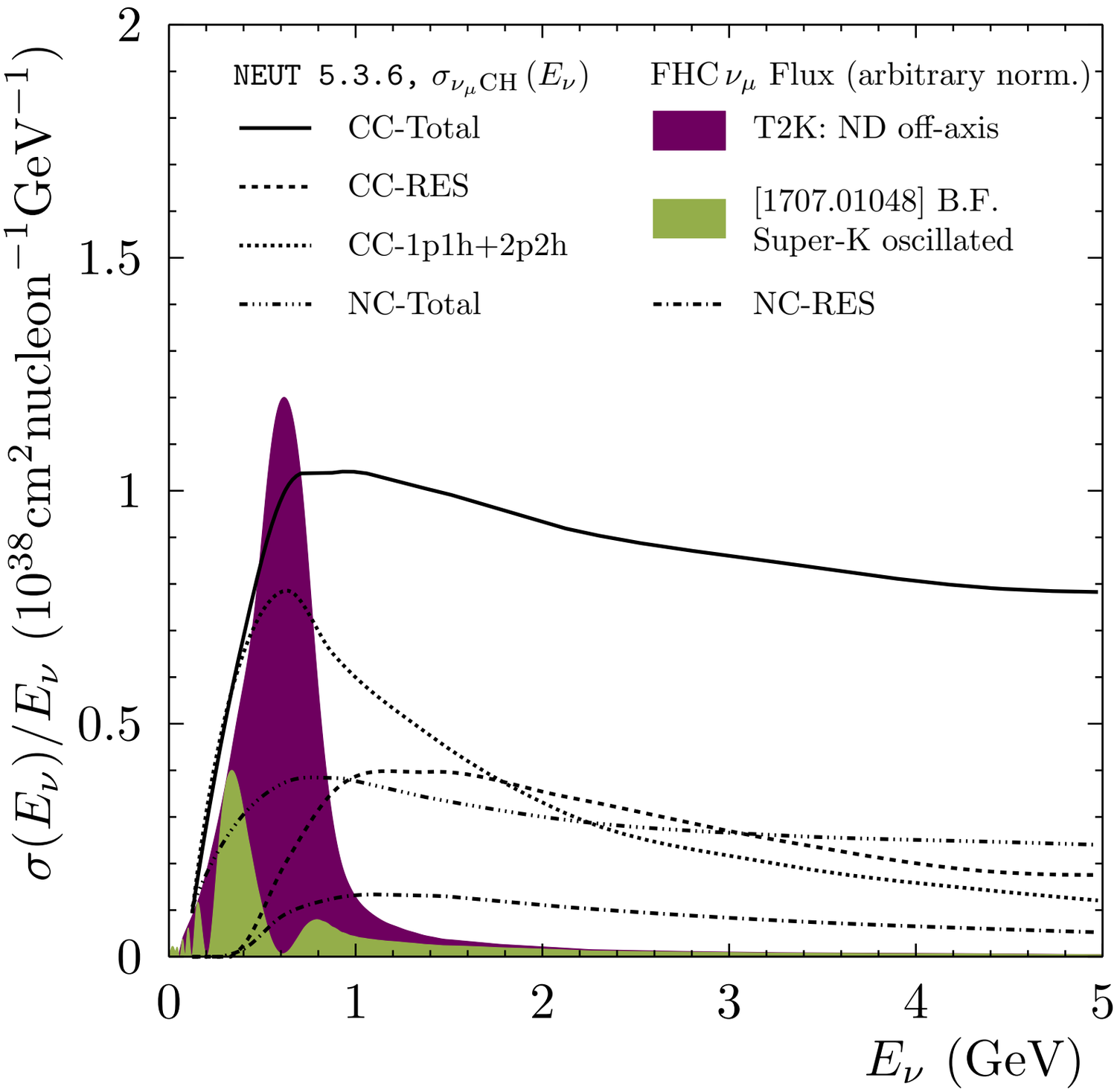
Cross section (true kinematics)

Efficiency (true kinematics)

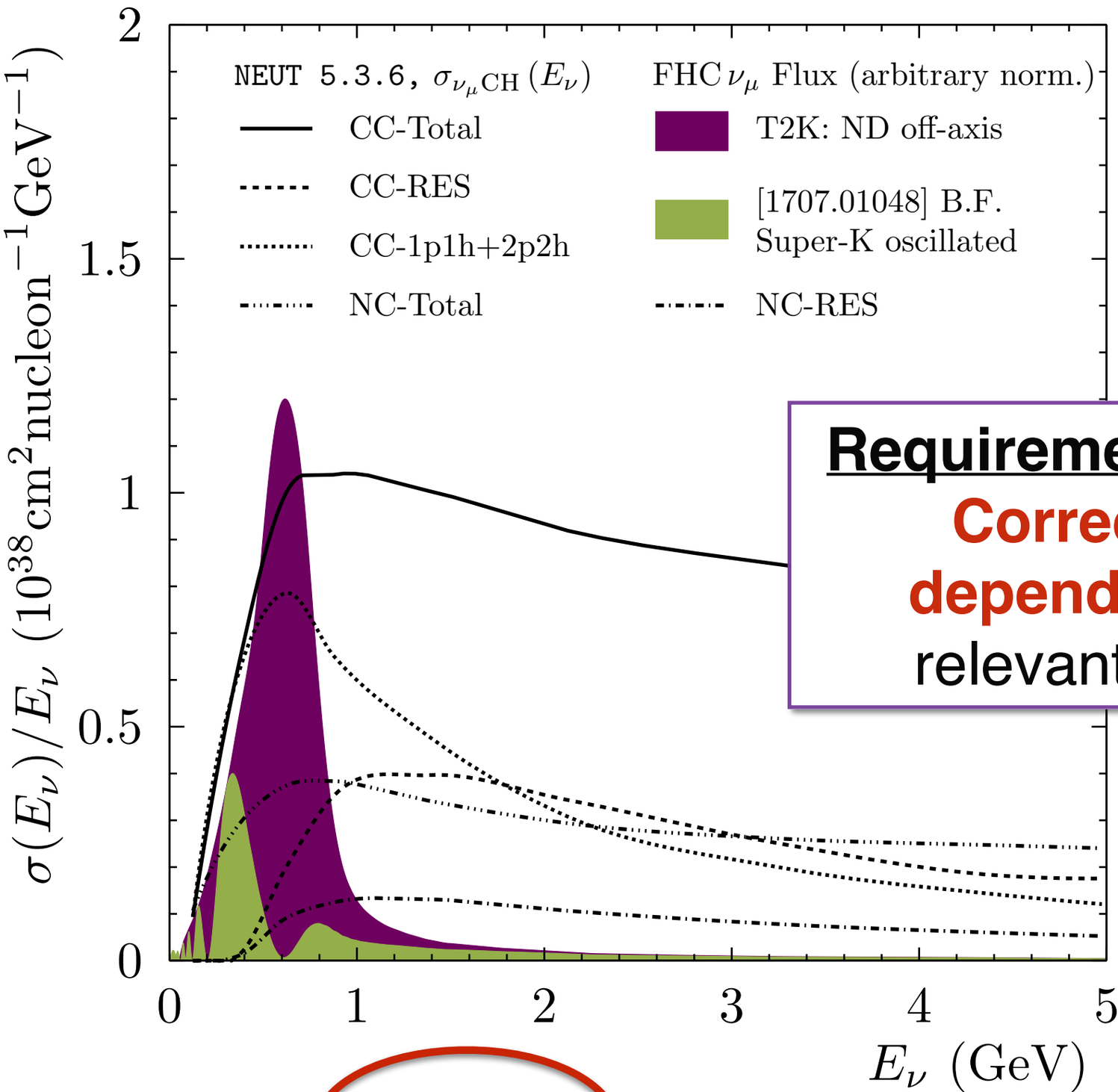
Relationship between true and reconstructed kinematics)

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Can’t isolate single processes: “wide beams”



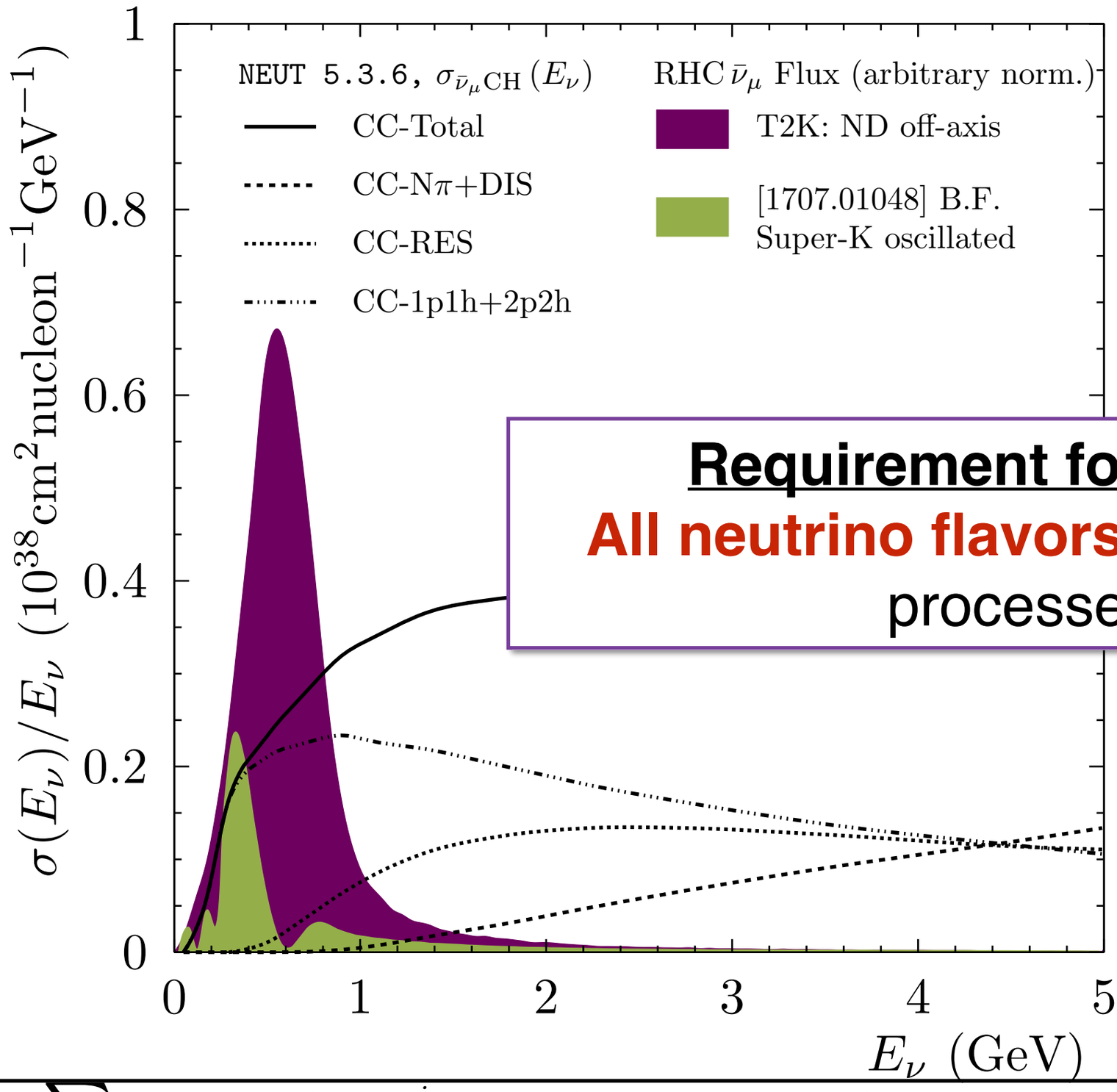
Incident energy is not known. Spread of beam is larger than nuclear effects.



Requirement for model:

Correct energy dependance for all relevant processes

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

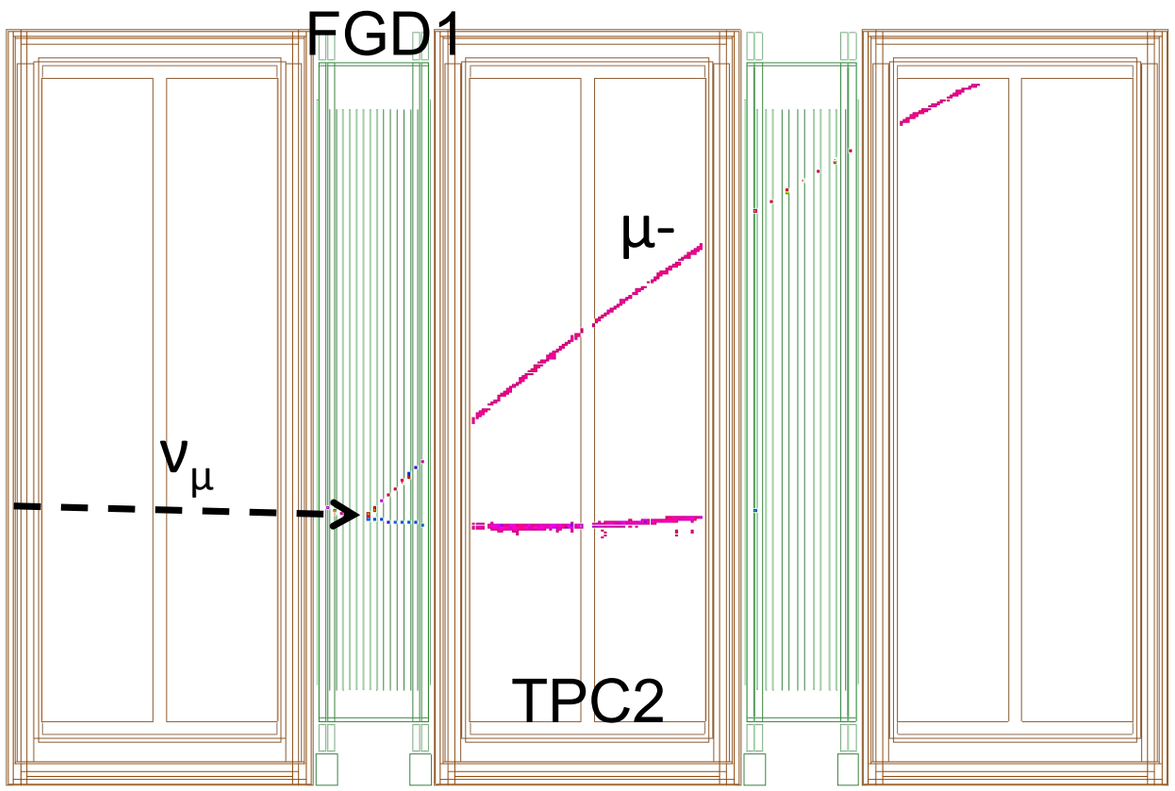


Requirement for model:

All neutrino flavors! for relevant processes

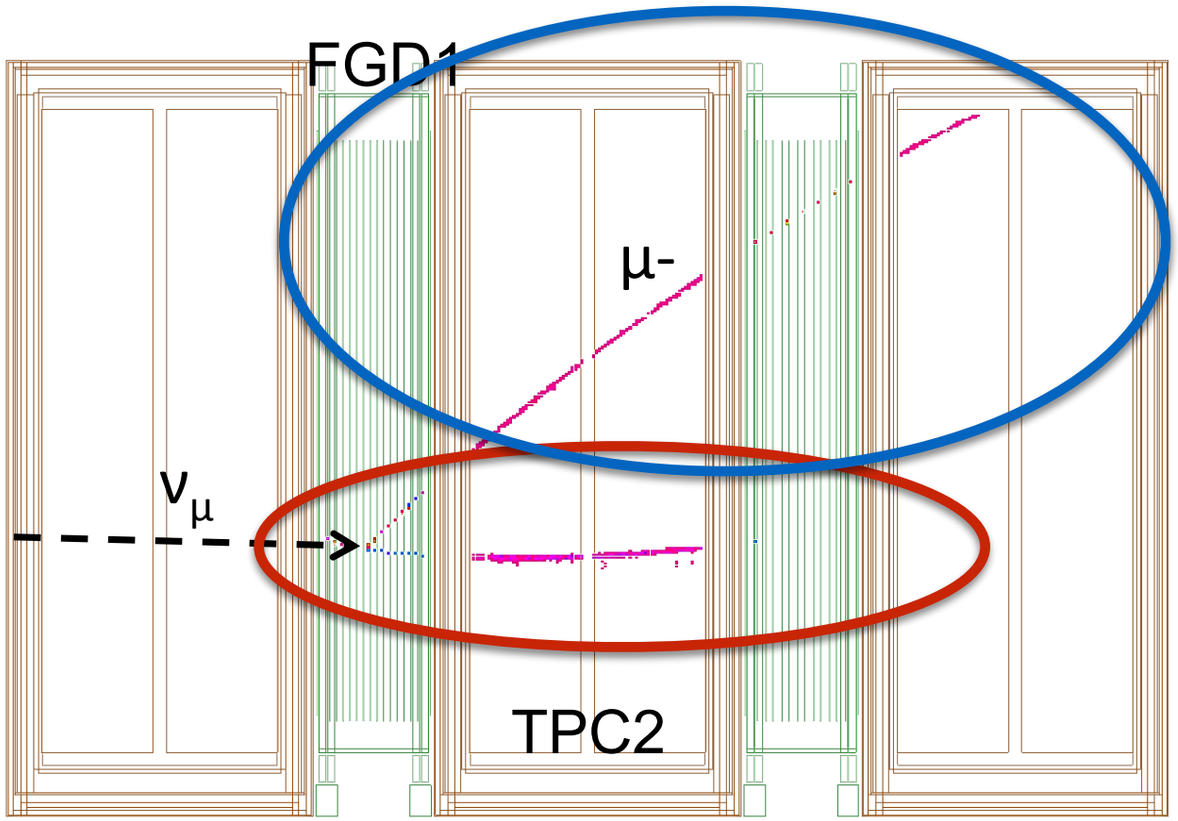
$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Need: hadronic state description



- T2K (off-axis, near detector) event display
- CC0π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Needs: semi to exclusive final states



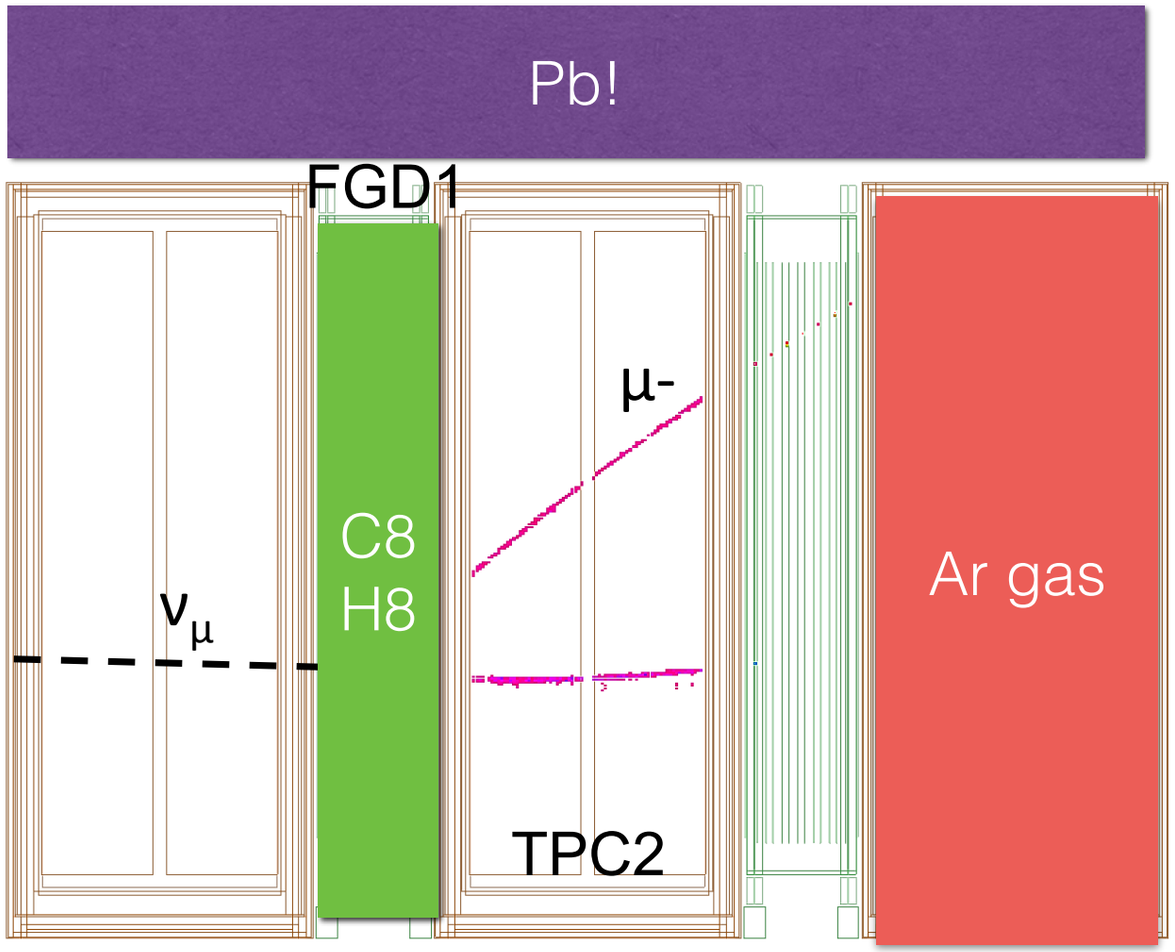
- T2K (off-axis, near detector) event display
- CC0π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Requirement for model:

- All visible particles for efficiency (background) and energy estimates

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Needs: target material



Target materials:

- T2K: H2O
- NOvA: CH+Cl
- SBN, DUNE: Ar

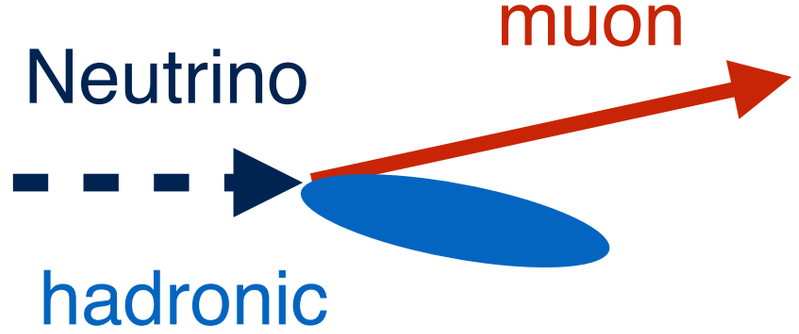
<u>Requirement for model:</u>

- Most nuclear targets, esp C, O, Ar

Needs: Energy estimation

- Oscillation depends on energy
  - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic}$$



T2K
Super-Kamiokande

SBN
DUNE

NOvA

Needs: Energy estimation

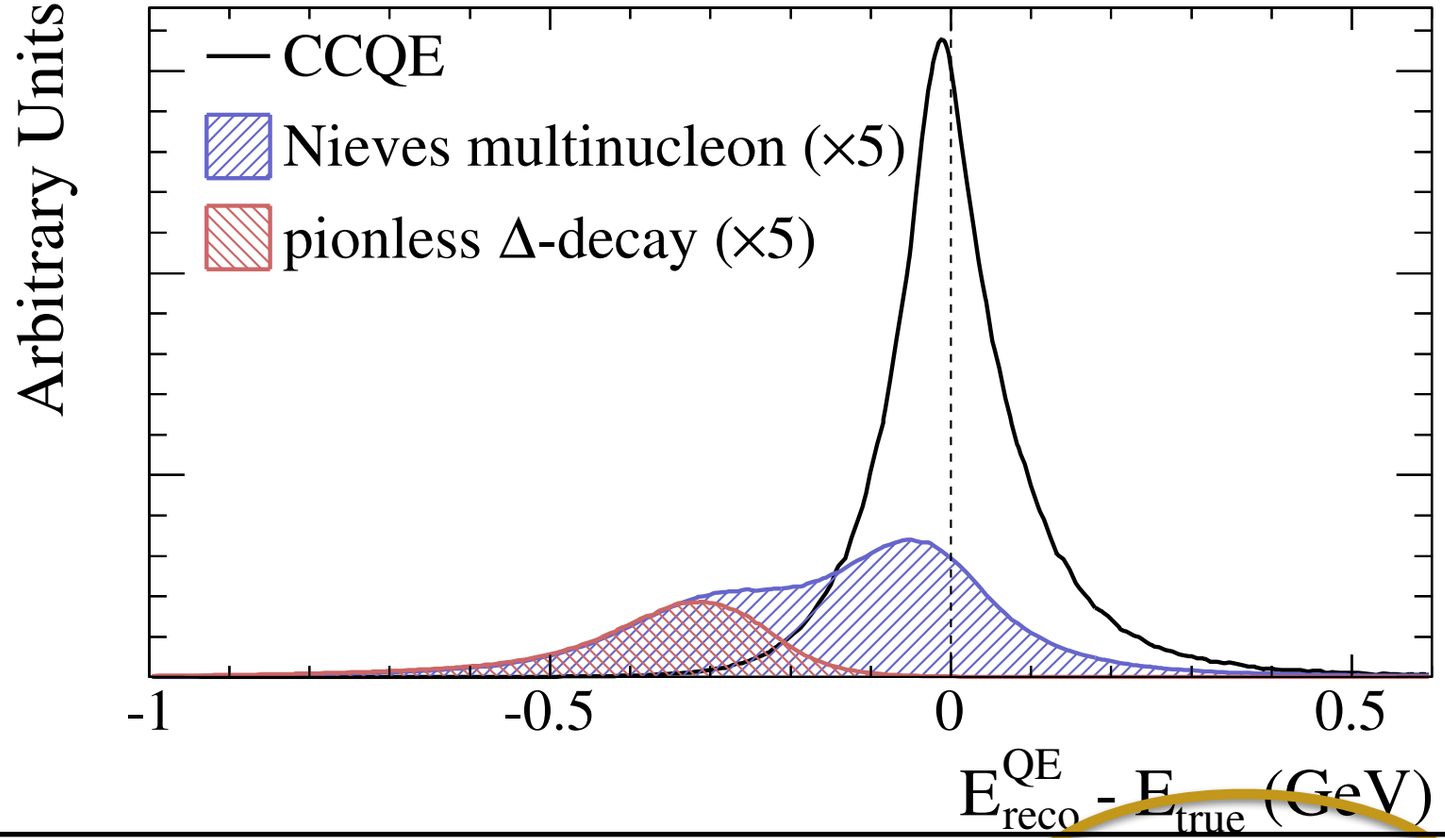
- Nuclear effects bias true and estimated neutrino energy

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

T2K, PRL 112, 181801 (2014)

Requirement for model:

- Correct mix of processes per topology
- true - reconstructed kinematic relationship



$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Near detectors

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model

Near detectors

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

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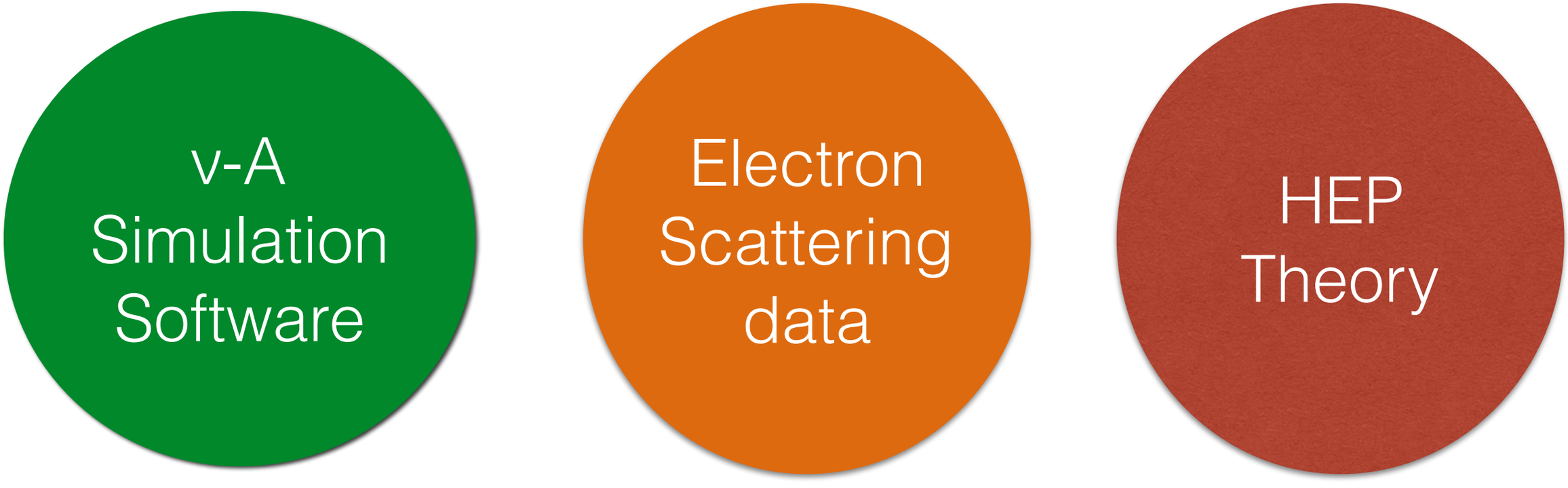
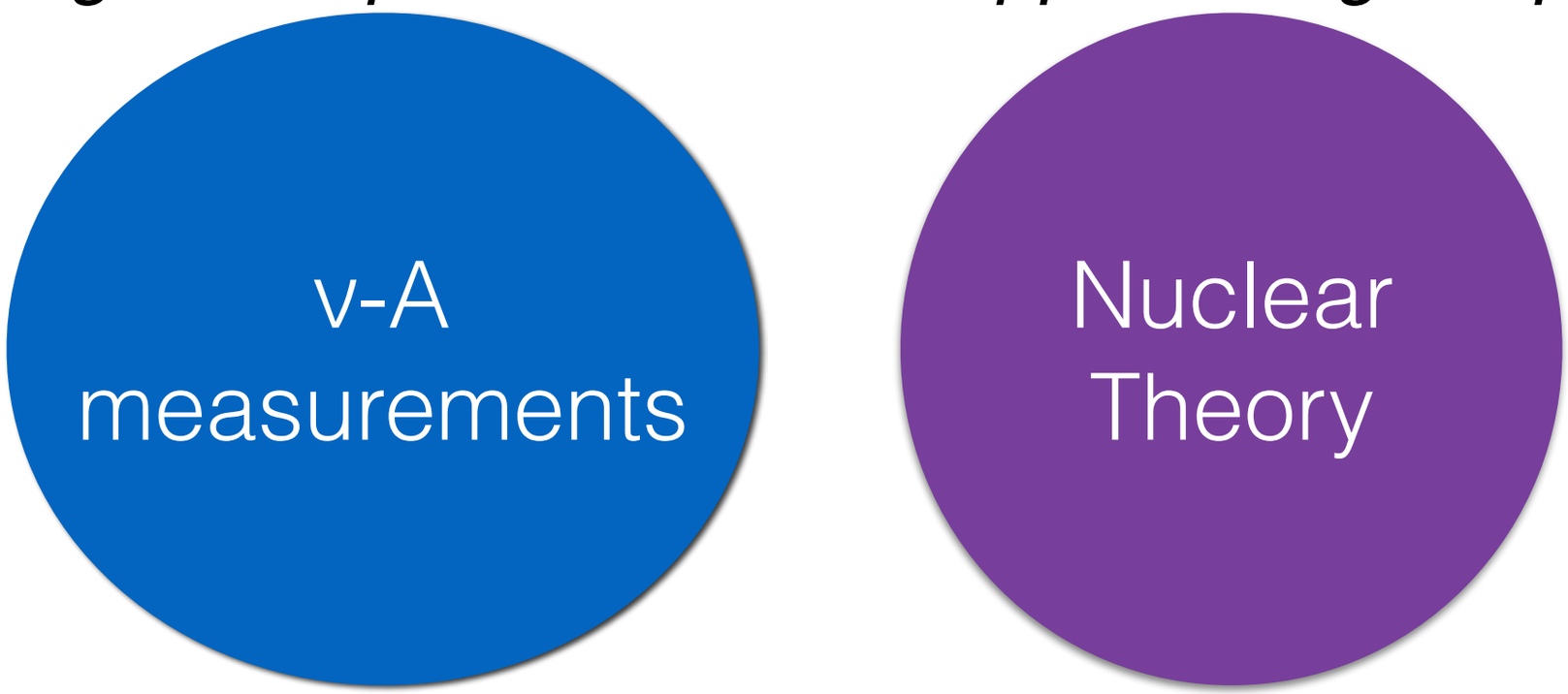
- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
- But, near detectors may not have the same: acceptance, backgrounds and **energy dependance** which all are corrected via a model

A view of the field



Challenge: Multiple communities approaching the problem



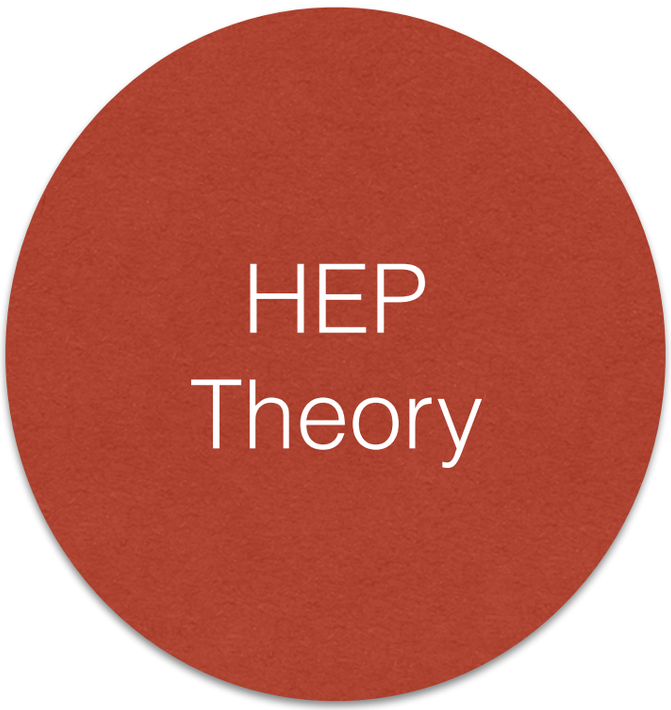
Recent NuSTEC white paper: *Prog. in Particle and Nuclear Physics, Volume 100 (2018)* arxiv1706.03621

A view of the field

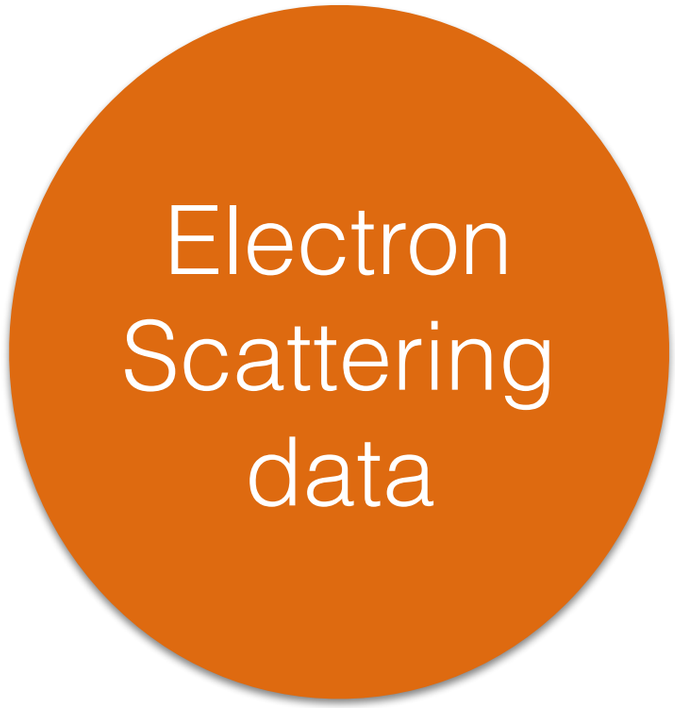
- Important theoretical developments from nuclear (e.g. SuSA, GFMC) or high energy theory (e.g. lattice QCD)

- Alliance between theorists and experimentalists (NuSTEC)

  - Subscribe nustec-news@fnal.gov (see backup)



A view of the field



- New measurements at JLab of Ar(40) spectral function [Phys.Rev. C99 no.5, 054608; Phys.Rev. C98 no.1, 014617]

- Data Mining Collaboration and E4Nu: release of CLAS electron scattering data; improvements and extensions to GENIE electron scattering interface

A view of the field

- Many neutrino interaction software programs (called “generators”) exist: GENIE, GiBUU, NEUT, NuWro

  - New: incorporation of latest models into software used by experiments (e.g. GENIE v.2.10, v3 [https://genie.hepforge.org/])

- Increased ease in comparing between models implemented and measurements relevant to cross sections (GENIE, NUISANCE [*JINST 12 no.01, P01016*])

A view of the field

- Unprecedented experimental information! ArgoNEUT, MicroBooNE, MINERvA, NOvA, T2K

- Coming soon: new information from neutrons (ANNIE, CAPTAIN) or lower thresholds (NINJA)

- Future: Near detectors for future experiments (Hyper-K, DUNE) and pseudo-monochromatic neutrino beam approach (NuPRISM, Ref [4])

Challenges of cross section measurements

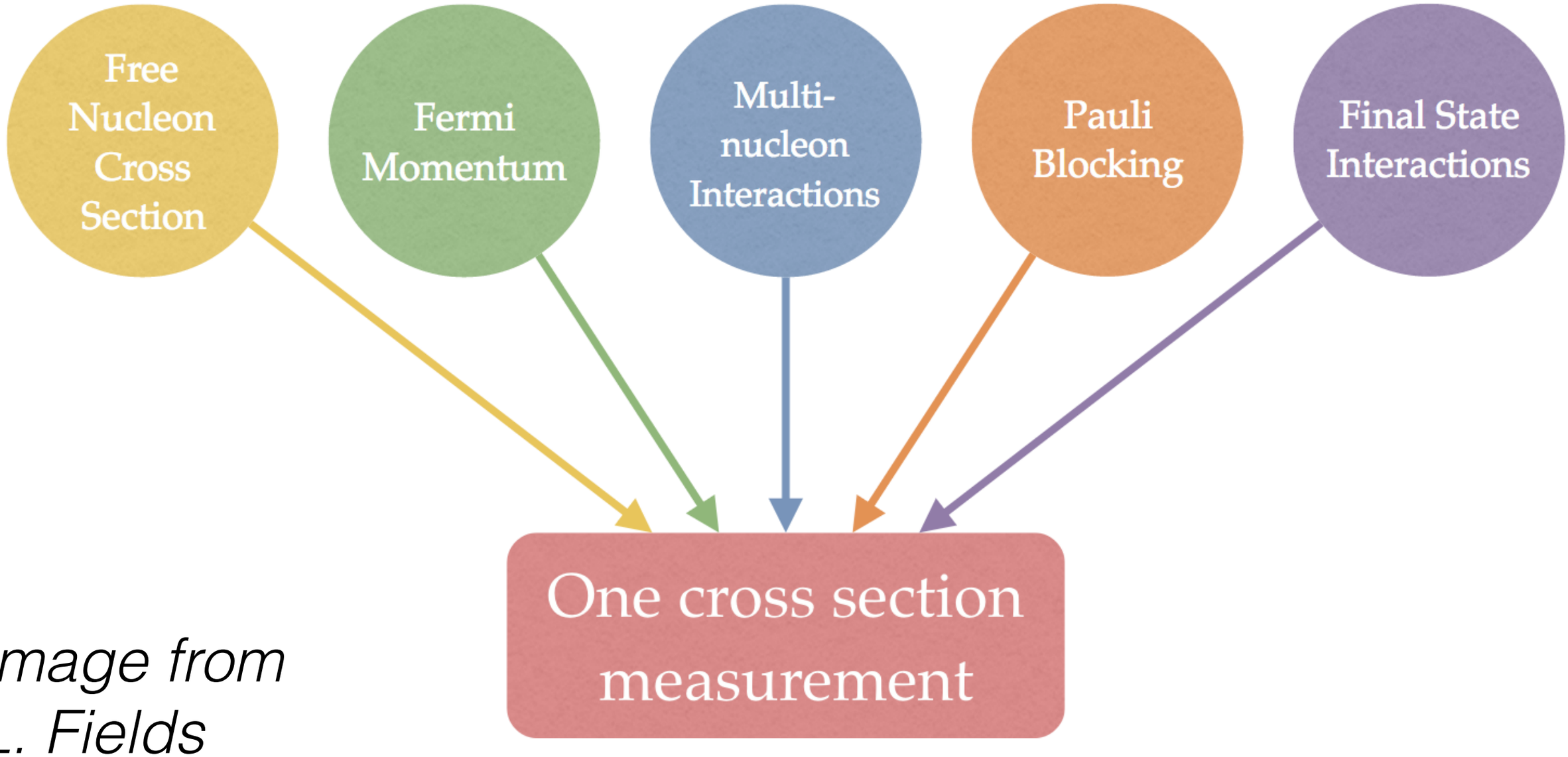


Image from L. Fields

- Measurements are sensitive to multiple physics effects on signal and background processes

It takes a village

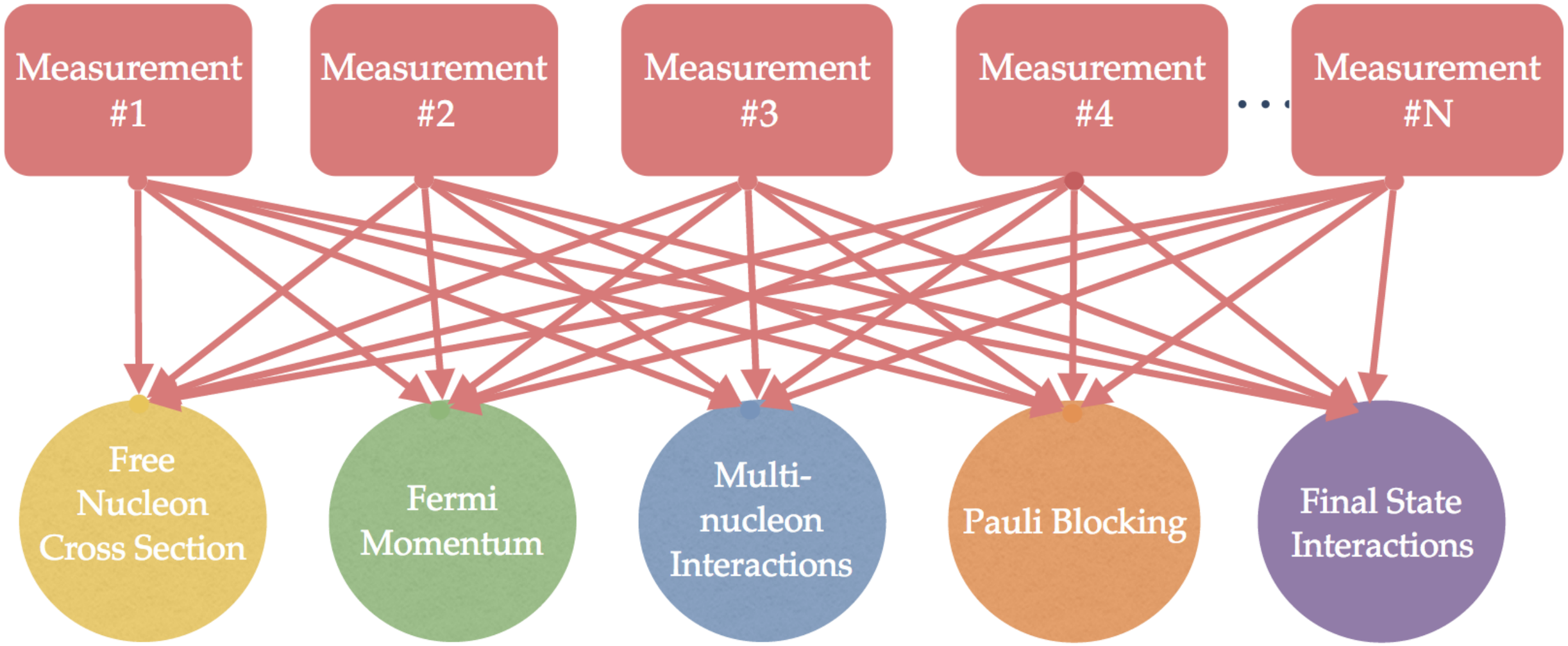
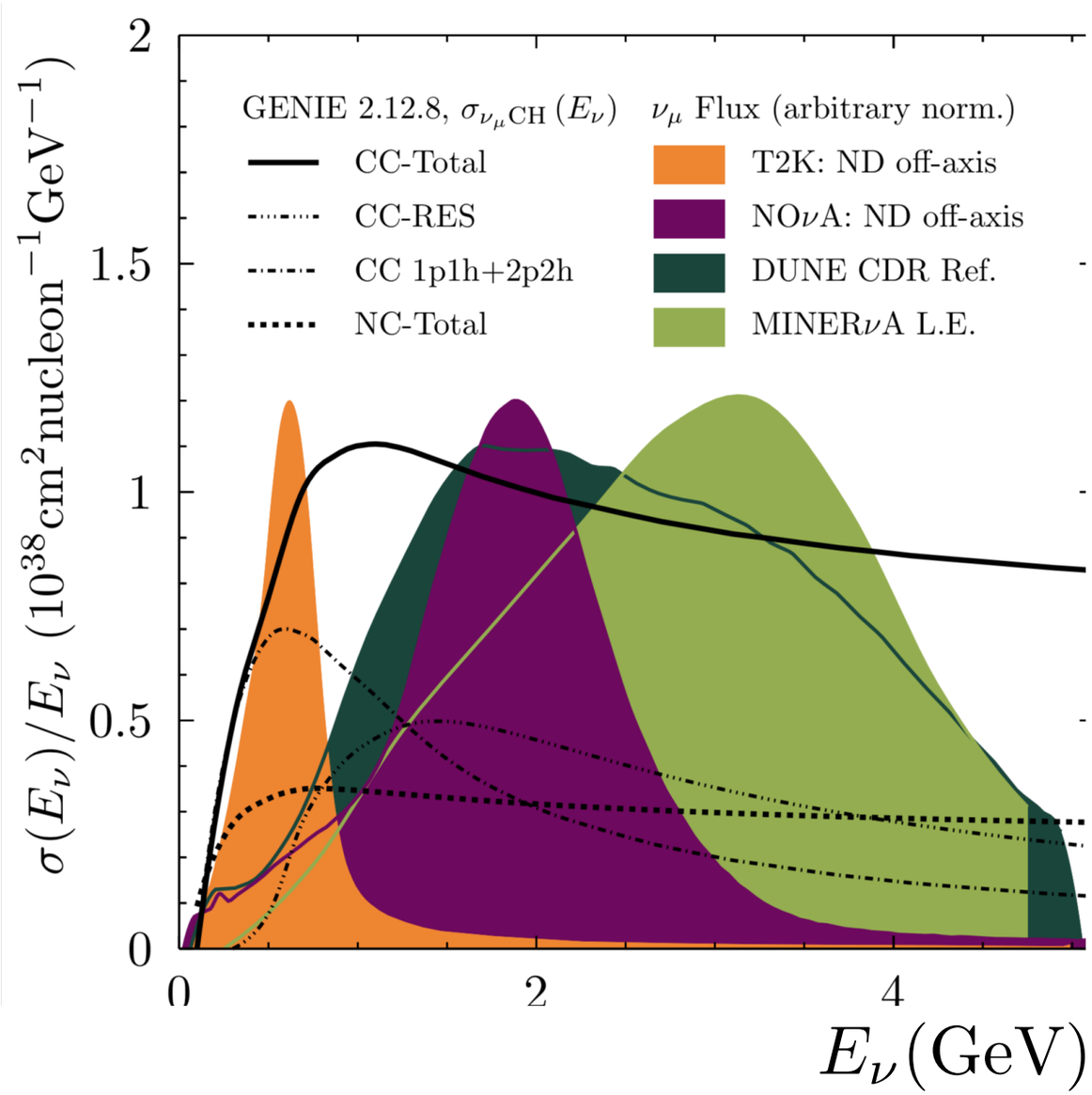


Image from L. Fields

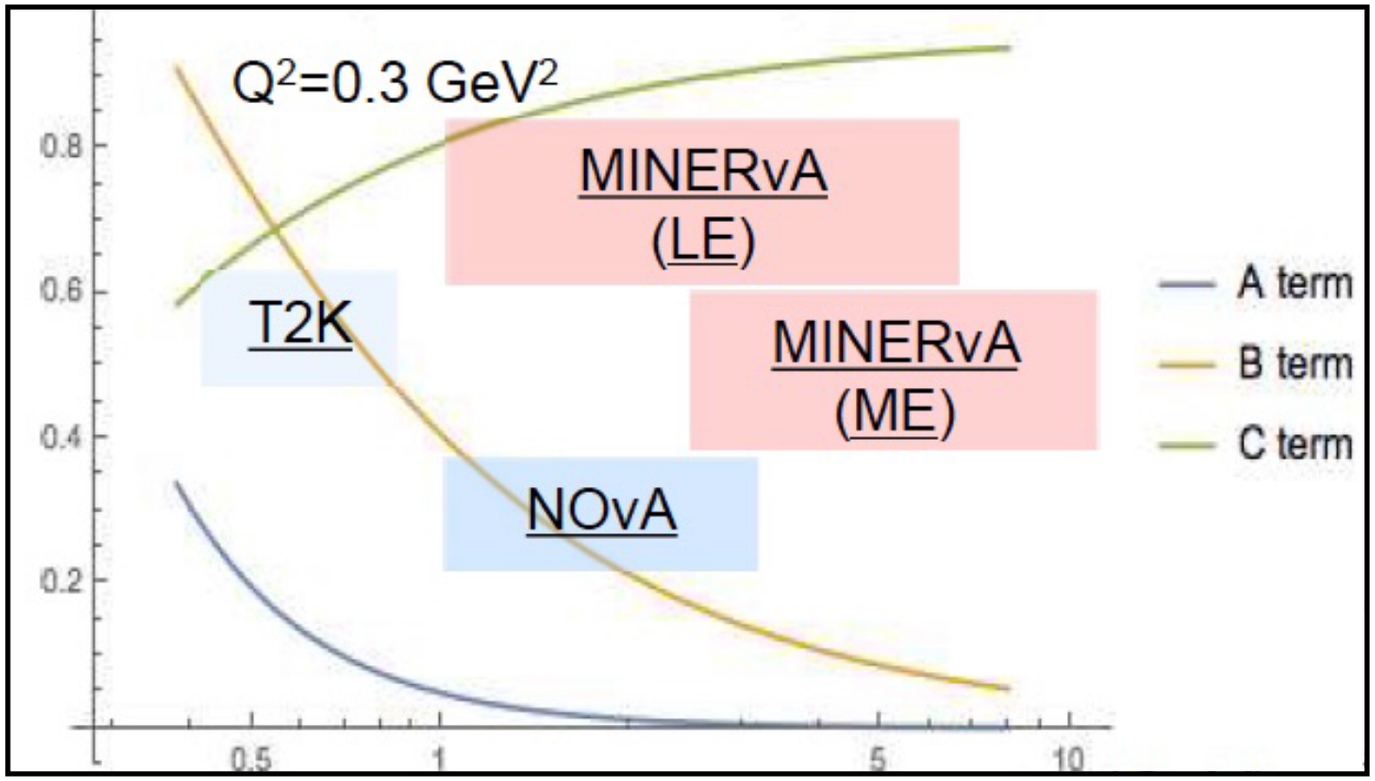
- Use many cross section measurements made with different beam energies + neutrinos and antineutrinos, target materials, topologies

Global program requires multiple measurements



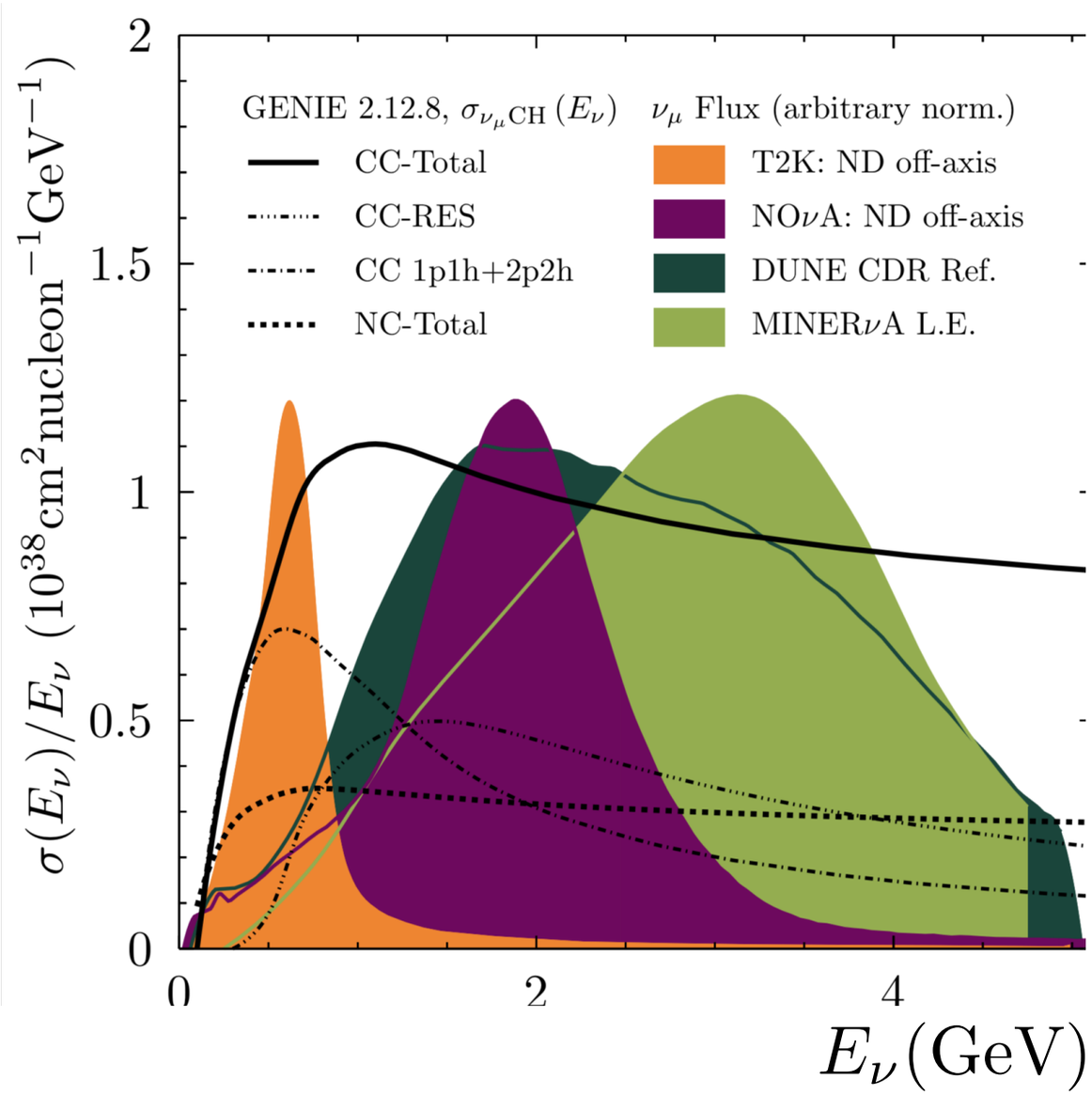
Ann. Rev. Nucl. Part. Sci. 68, 105 (2018)

dσ/dQ² vs. E_ν: QE, single nucleon (McFarland, Ruterbories)



$$E_\nu^2 \frac{d\sigma}{dQ^2 d\nu} = \check{A} + \check{B}E_\nu + \check{C}E_\nu^2$$

Global program requires multiple measurements



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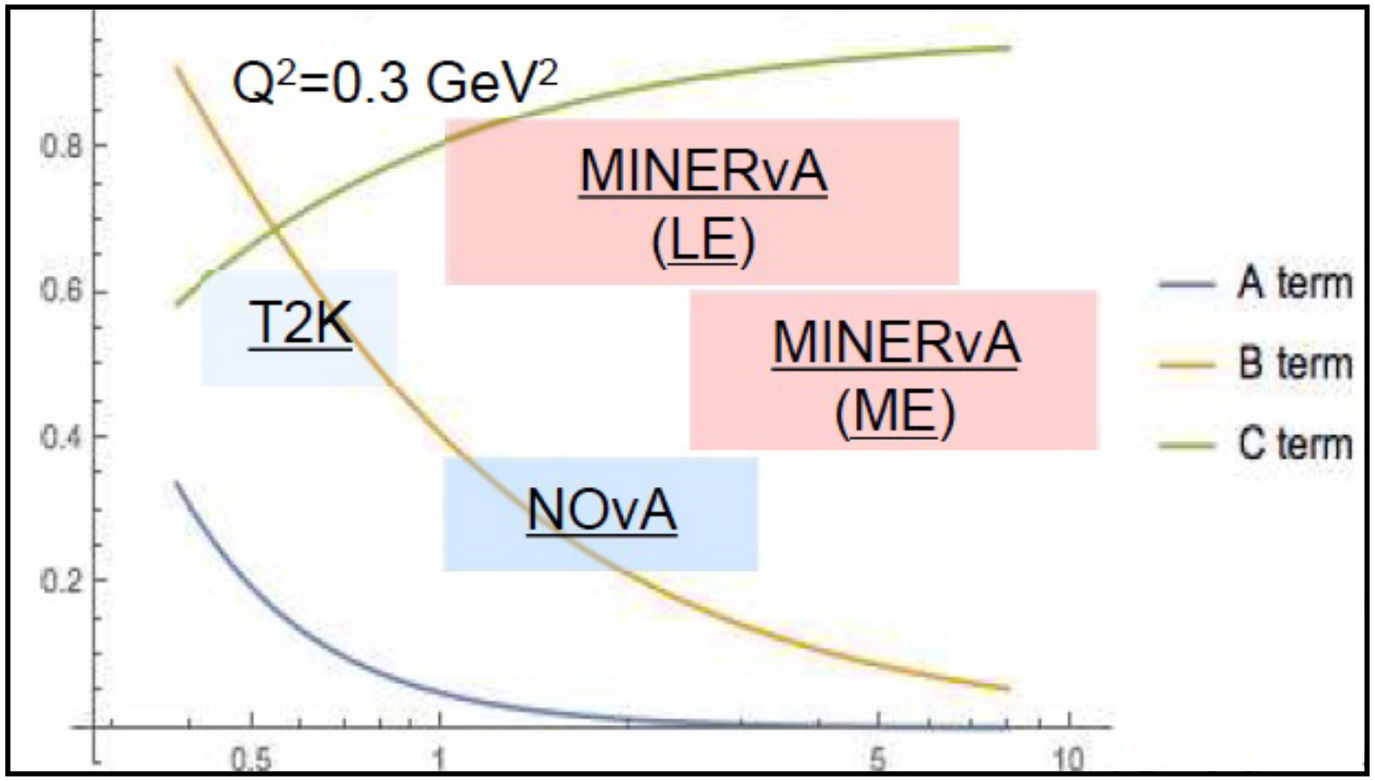


$$E_\nu^2 \frac{d\sigma}{dQ^2 d\nu} = \check{A} + \check{B}E_\nu + \check{C}E_\nu^2$$

Osc experiment	Target	cross sections from
T2K, NOvA	Scintillator	T2K, NOvA ND, MINERvA LE, HE
T2K, SK, IceCube	Water	T2K (INGRID, WAGASCI, ND280), MINERvA
DUNE	Ar	T2K ND upgrade, MicroBooNE/SBN, MINERvA

Outline

Recent results in neutrino cross section experiments

Outline

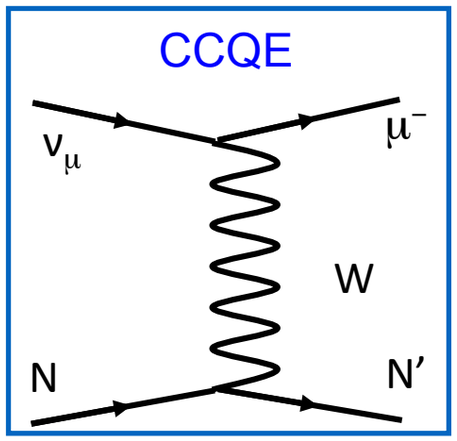
Credit? T. Katori, artistic representation of cross sections

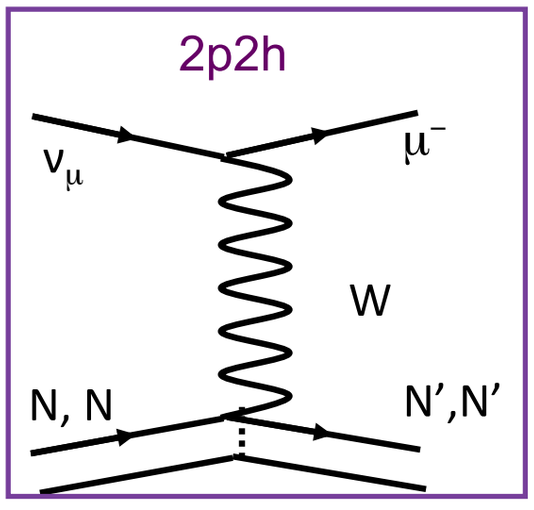
Recent results in neutrino cross section experiments

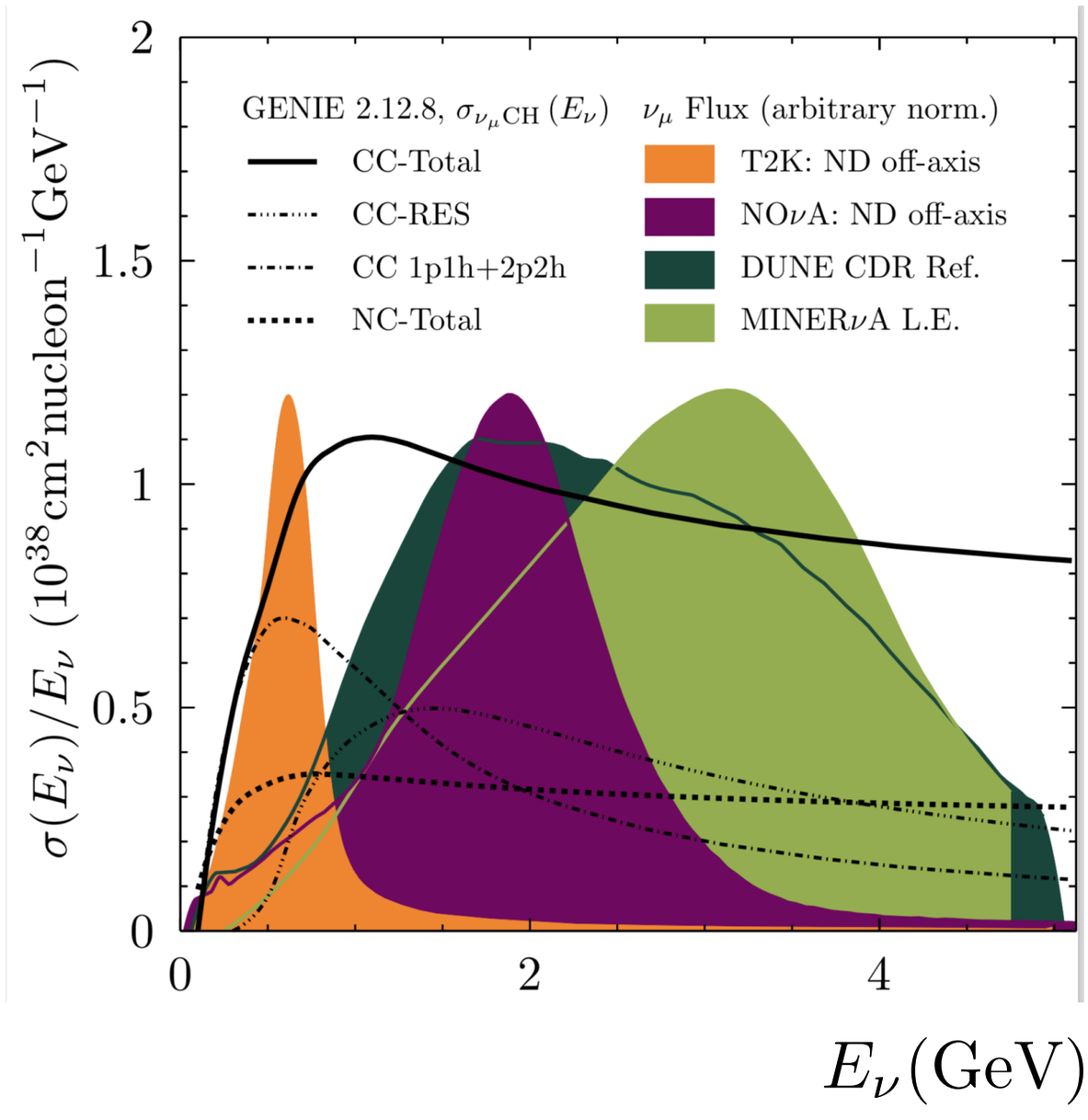
These experiments are difficult and subtle.

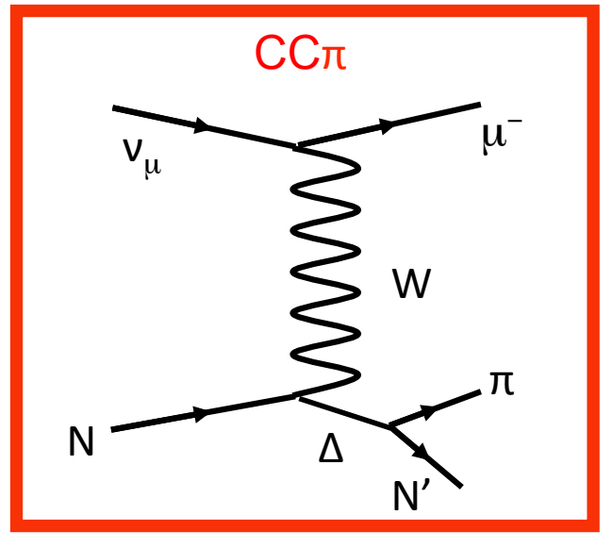
Important details in experiment websites, detector papers, or physics papers.

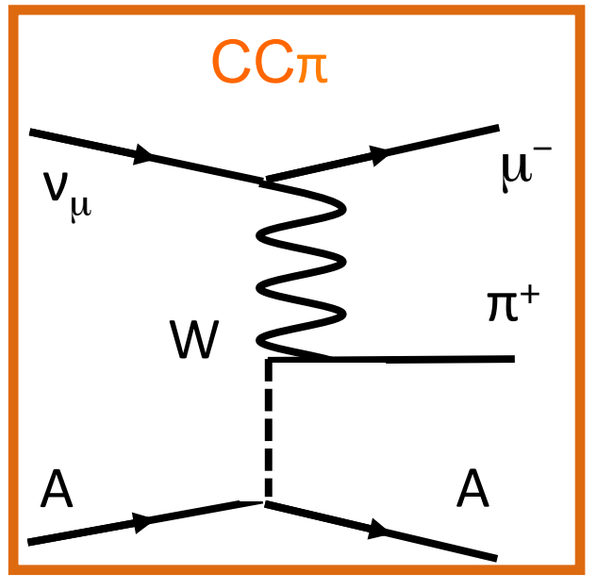
Shameless advice from KM: Ann.Rev.Nucl.Part.Sci. 68 (2018) 105-129





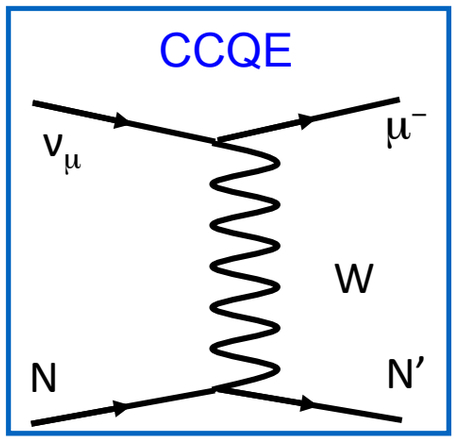


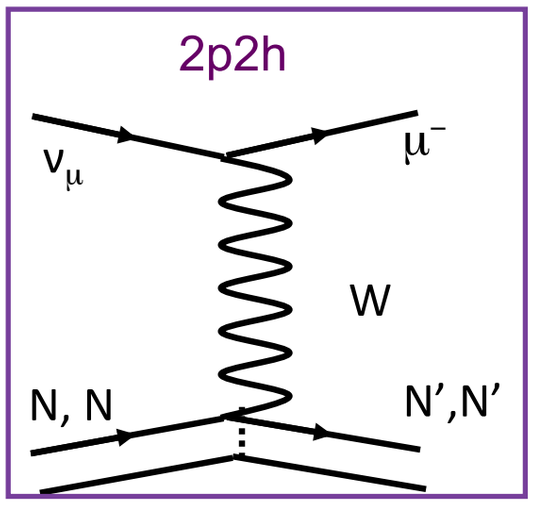


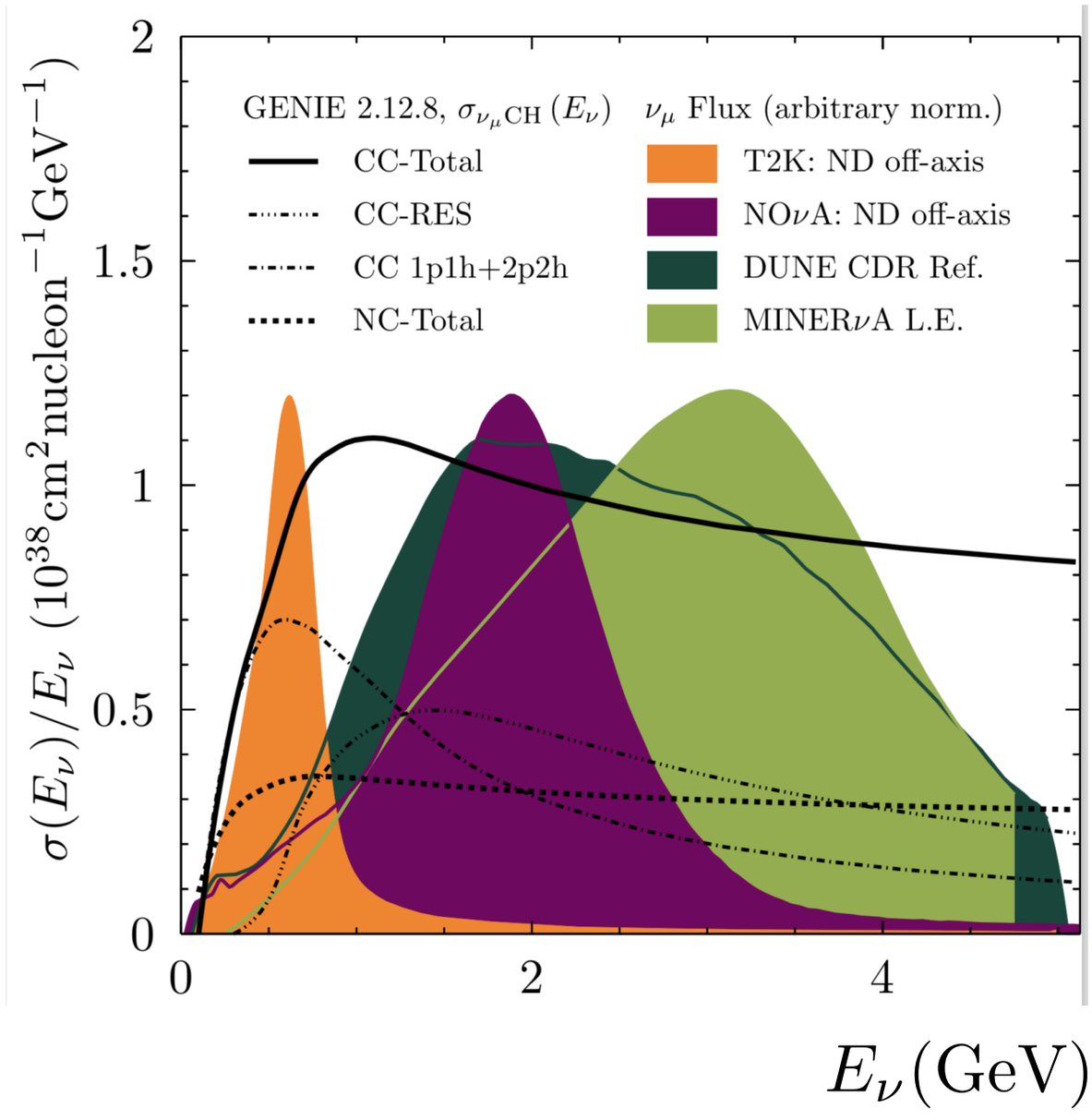


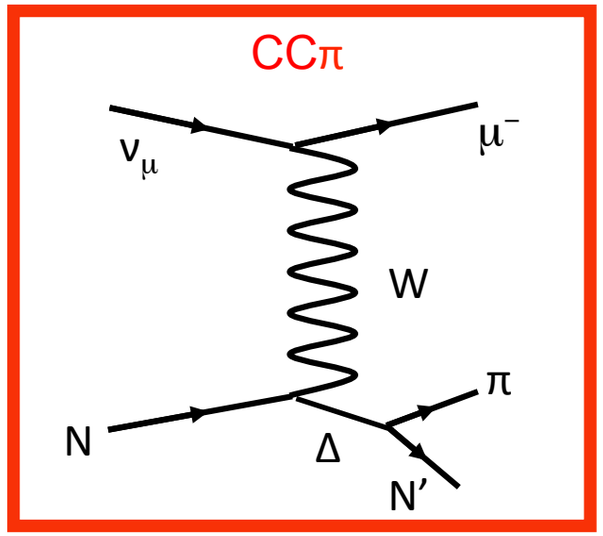
+ CC inclusive

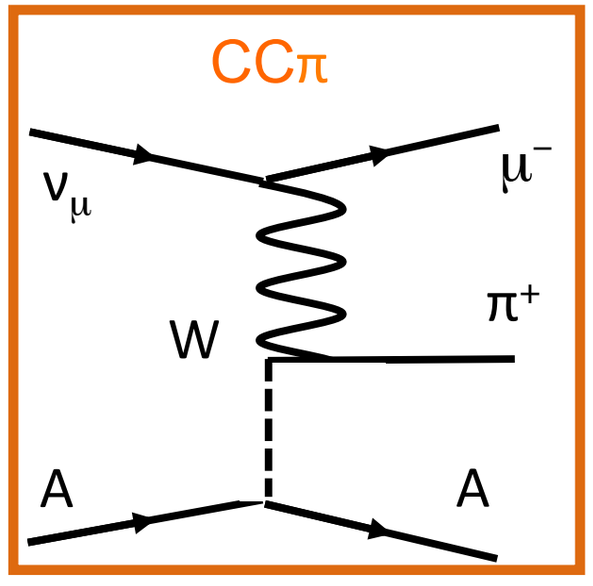
+ NC







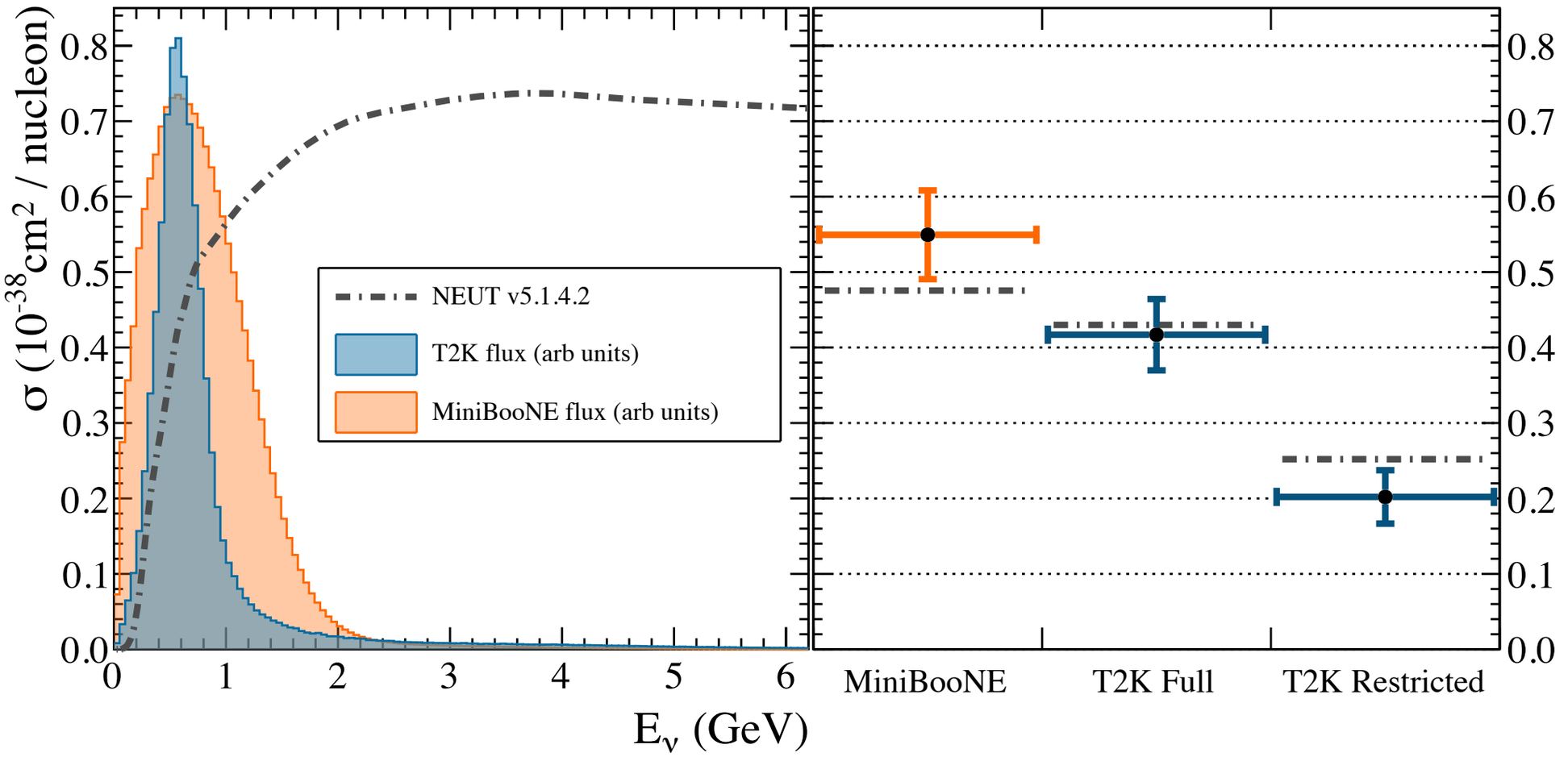


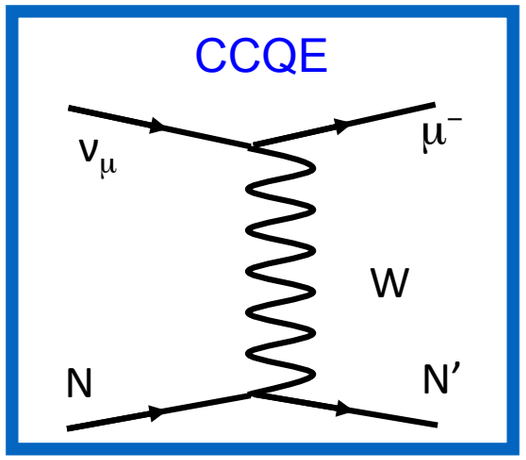


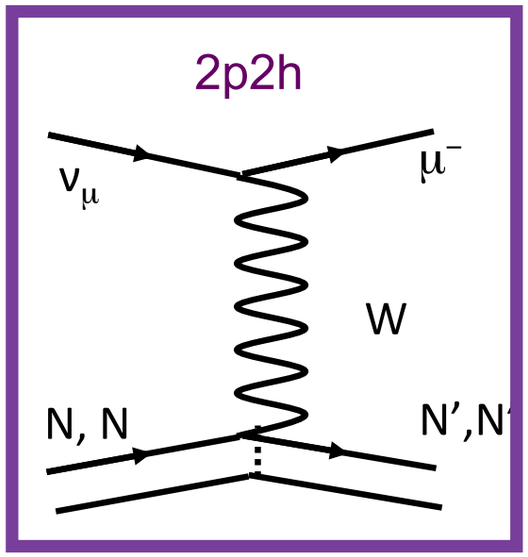
This is a picture centered on oscillation.

Important measurements by MINERvA for rare kaon production for proton decay:
Phys. Rev. D 94, 012002; Phys. Rev. Lett. 117, 061802; Phys. Rev. Lett. 199, 011802

“QE puzzle”





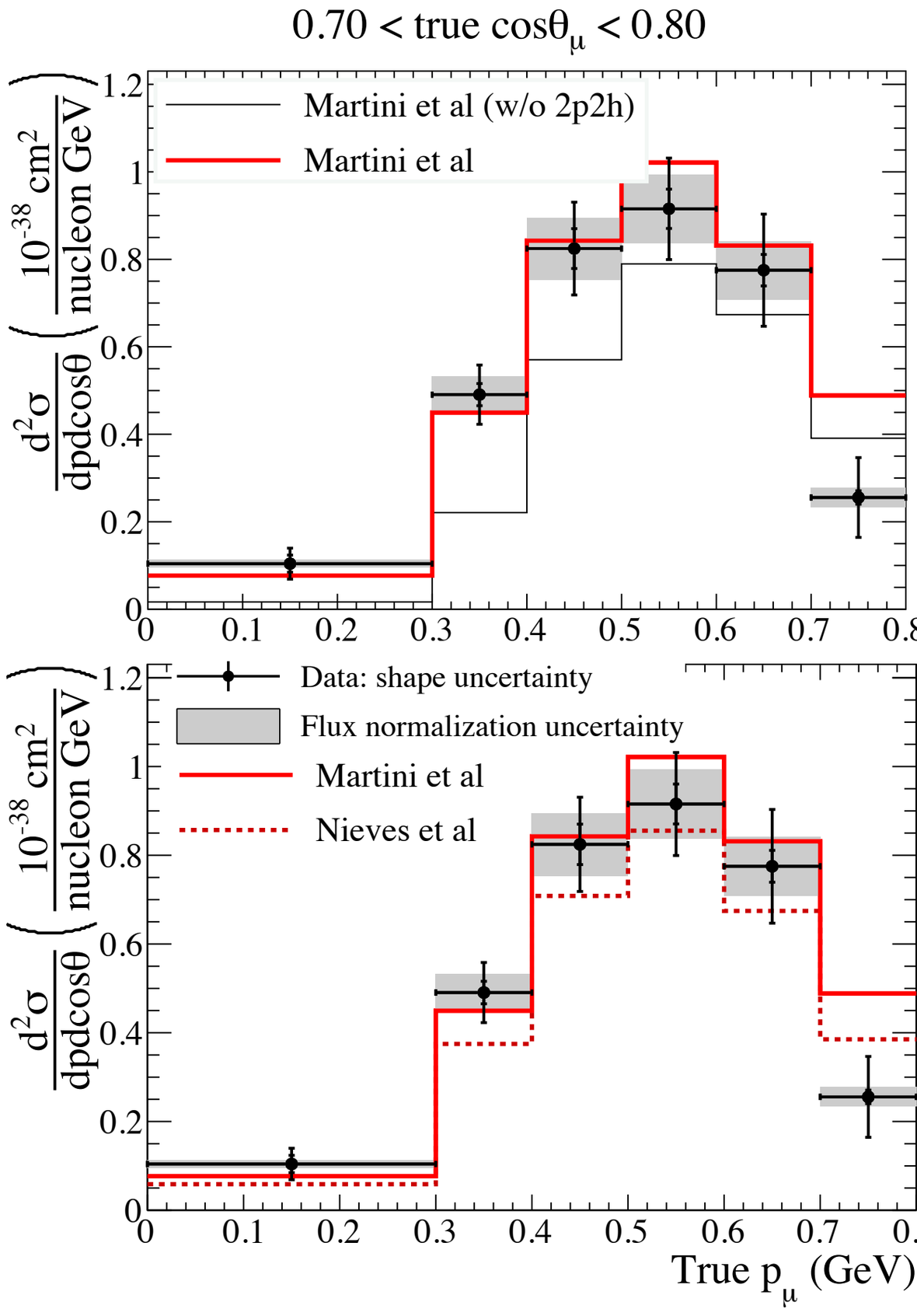


- CCQE-like process important for T2K, NOvA, DUNE, Hyper-K, SBL programs
- “QE puzzle”: MiniBooNE results at odds with higher energy measurements, single nucleon models - *Phys.Rev. D93 (2016) no.7, 072010*
- T2K analysis consistent between MiniBooNE: **higher QE-like cross section suggestive of presence of nuclear effects**, including 2p2h processes

T2K QE-like differential results

- Detailed information (cross section in muon kinematics) **compared to latest QE and 2p2h models**

Phys. Rev. D 93, 112012 (2016)

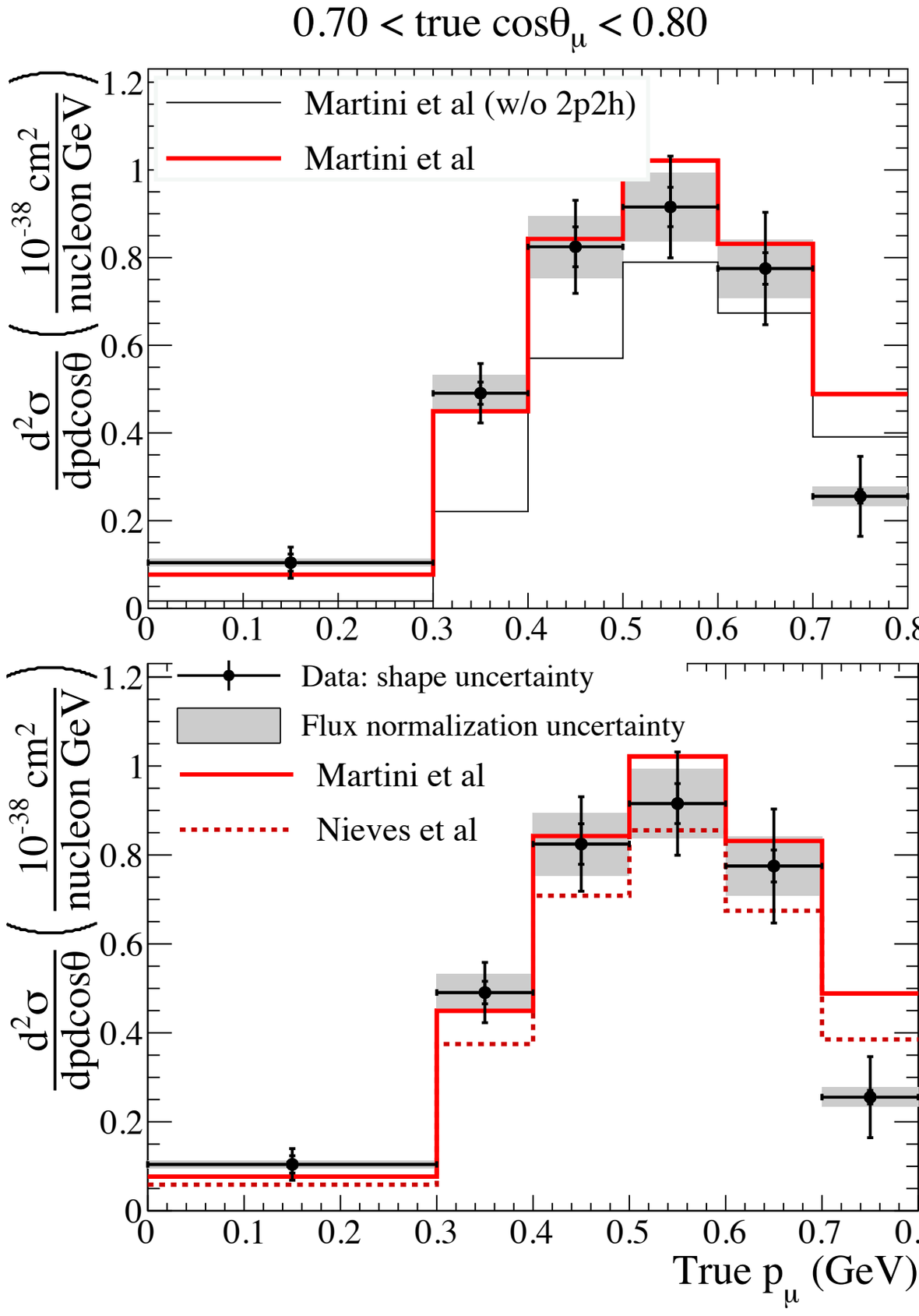


T2K QE-like differential results

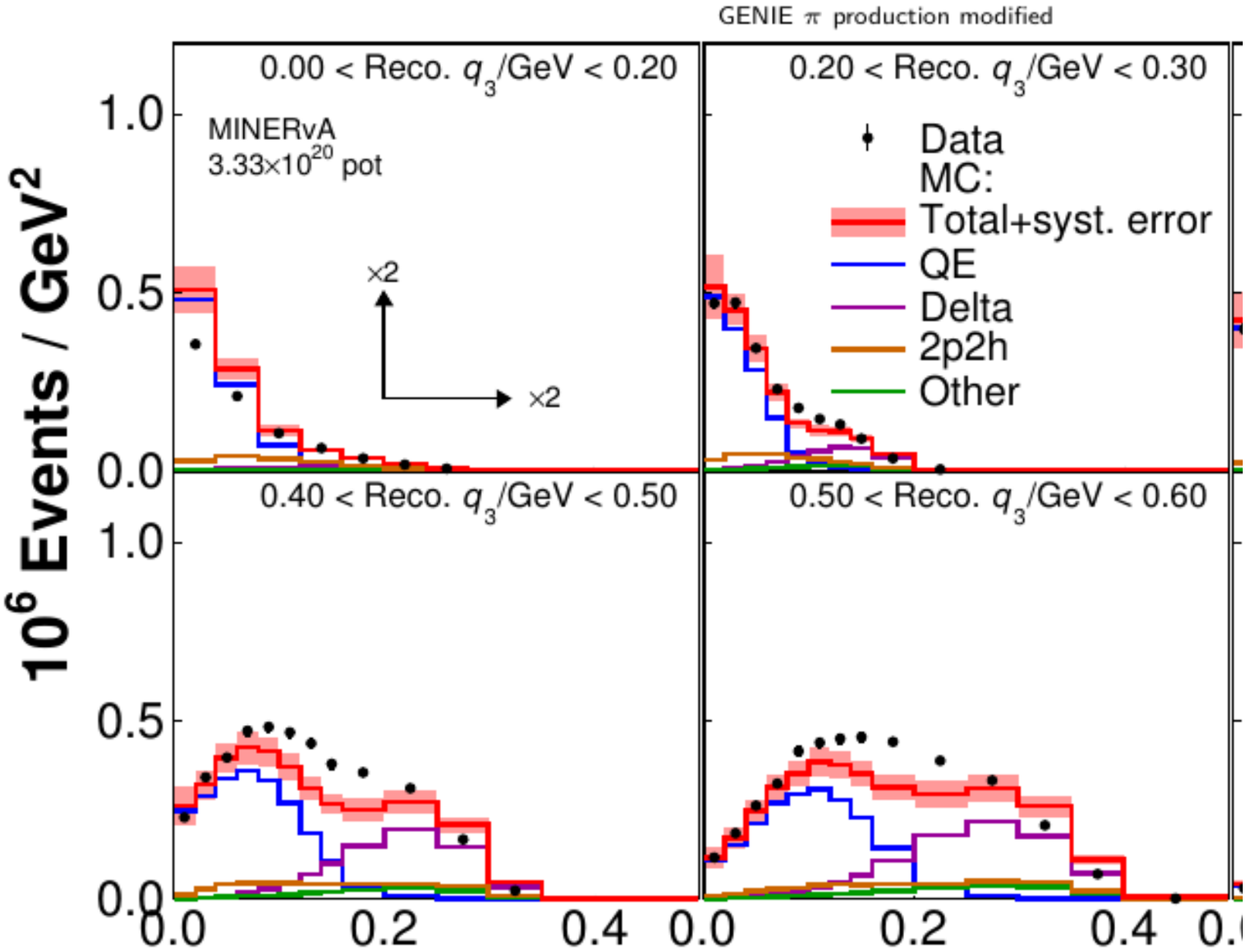
- Detailed information (cross section in muon kinematics) **compared to latest QE and 2p2h models**

"0π" final state (to match MiniBooNE, T2K far detector results)

CH target; new results also on water/oxygen



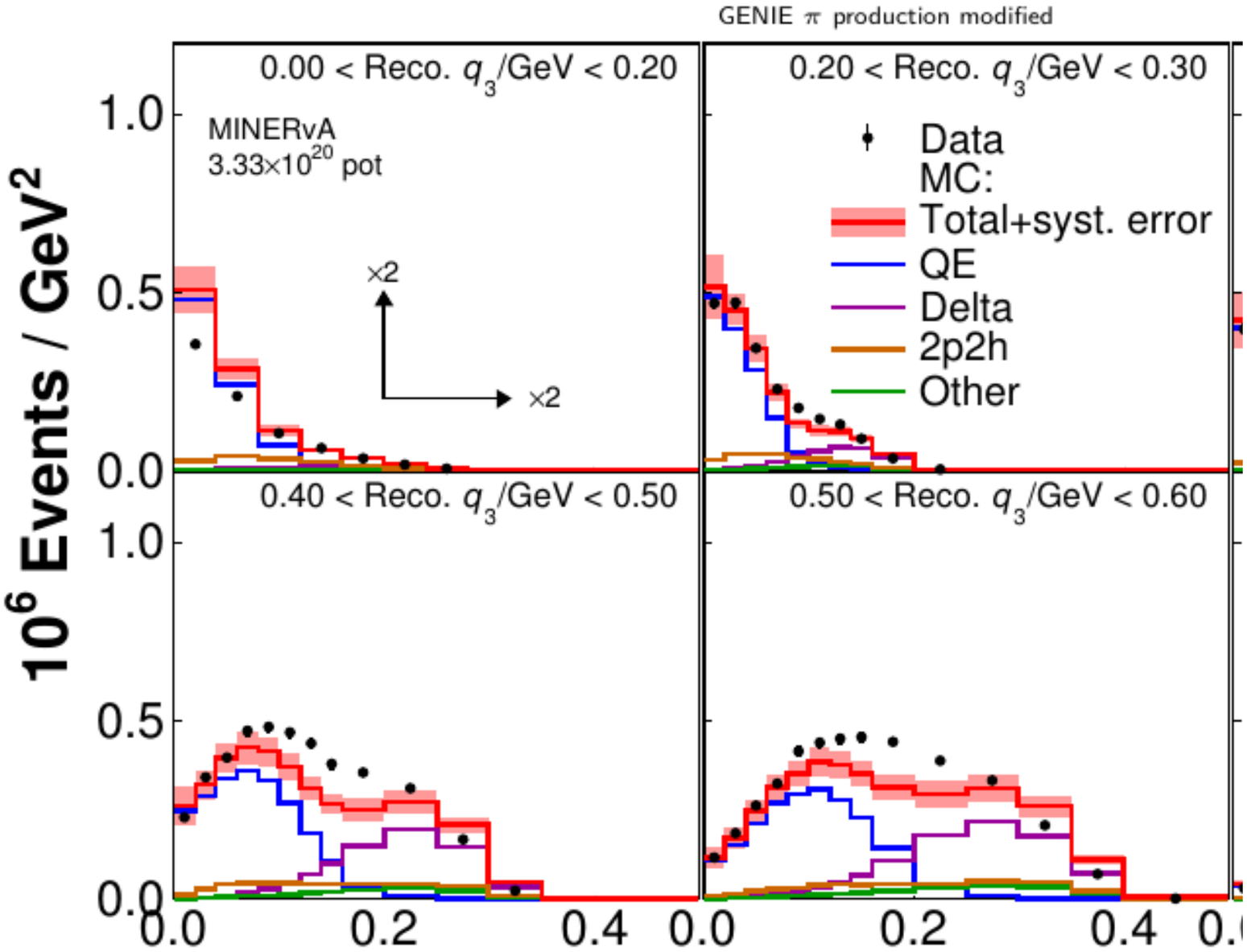
Novel MINERvA Test of Nuclear Effects



PRL 116, 071802 (2016), plot from NuInt2017

- CC inclusive selection with low recoil energy, use estimate of available energy from all charged particle tracks (proton, pion, muon)

Novel MINERvA Test of Nuclear Effects

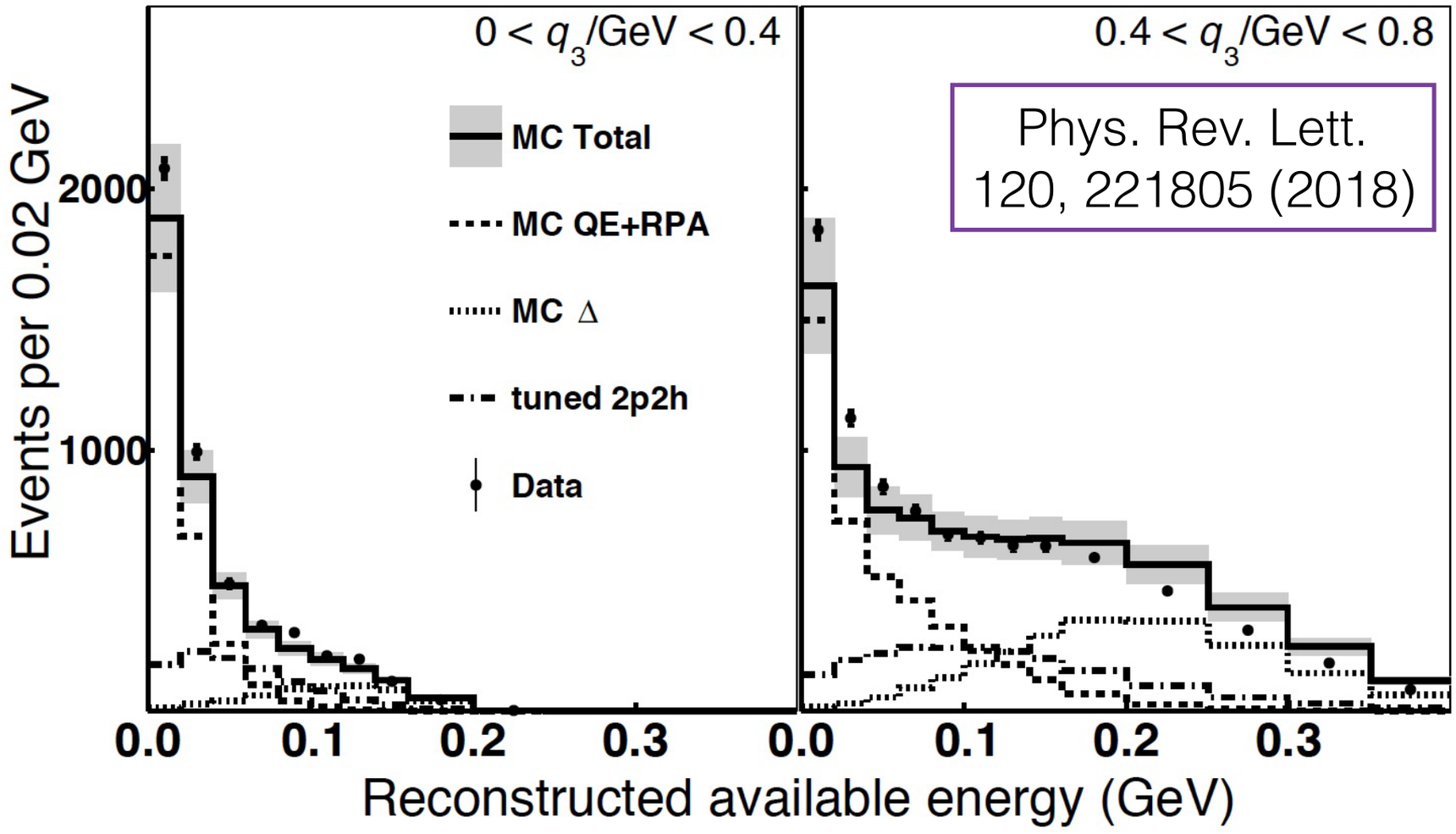


PRL 116, 071802 (2016), plot from NuInt2017

2p2h model needed, and also not "enough"

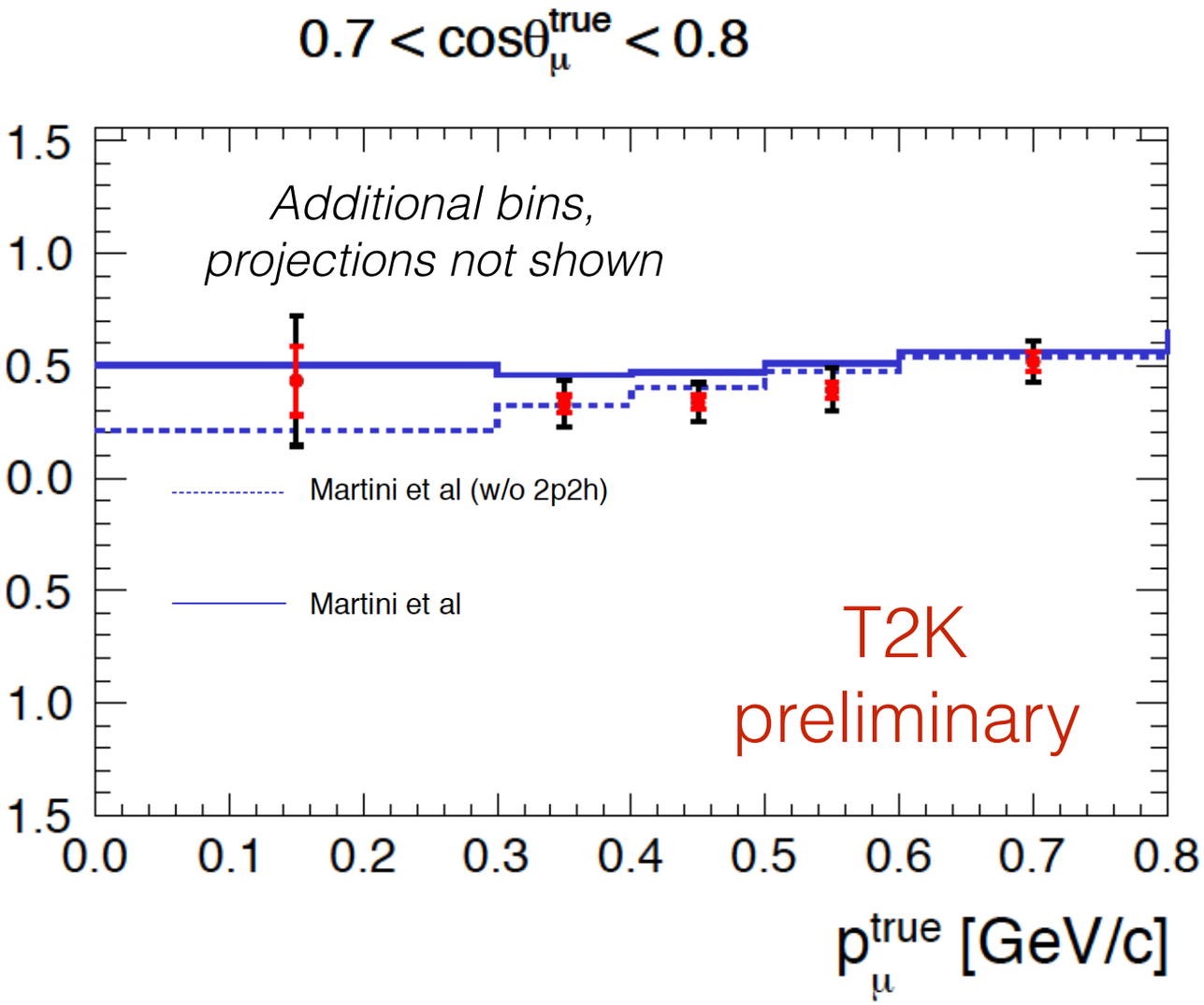
- CC inclusive selection with low recoil energy, use estimate of available energy from all charged particle tracks (proton, pion, muon)

MINERvA low recoil: antineutrino results



Progress?! MINERvA empirical fit to low recoil neutrino data also resolves antineutrino data disagreements

T2K combined result: neutrino and antineutrinos



CC0π on CH, off-axis flux neutrinos and antineutrinos

- Difference in sign of neutrino and antineutrino cross section is axial-vector interference term

Pieces of the QE puzzle

Muon kinematics (neutrino)

Calorimetric energy deposition

Multiple beam energies

Muon kinematics (antineutrino)

Pieces of the QE puzzle

Muon kinematics (neutrino)

Calorimetric energy deposition

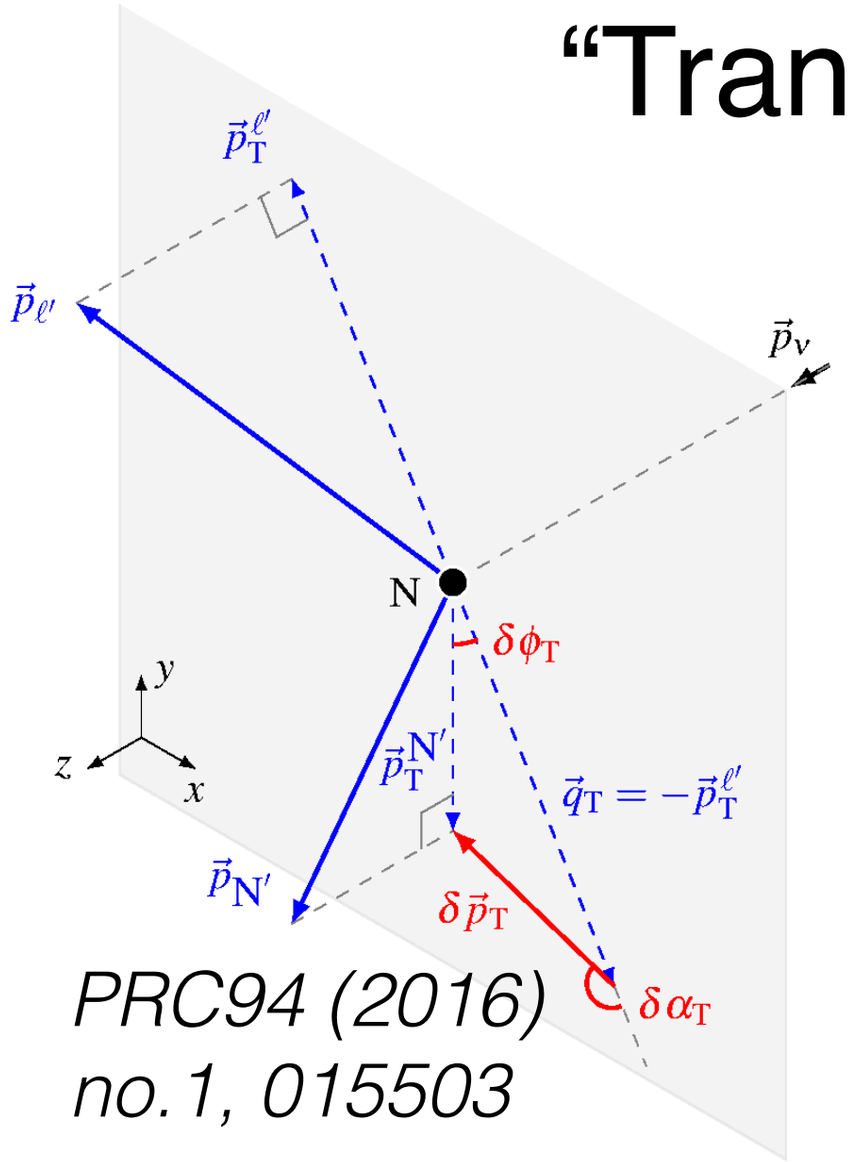
Multiple beam energies

Muon kinematics (antineutrino)

Muon-proton correlations

Neutrons

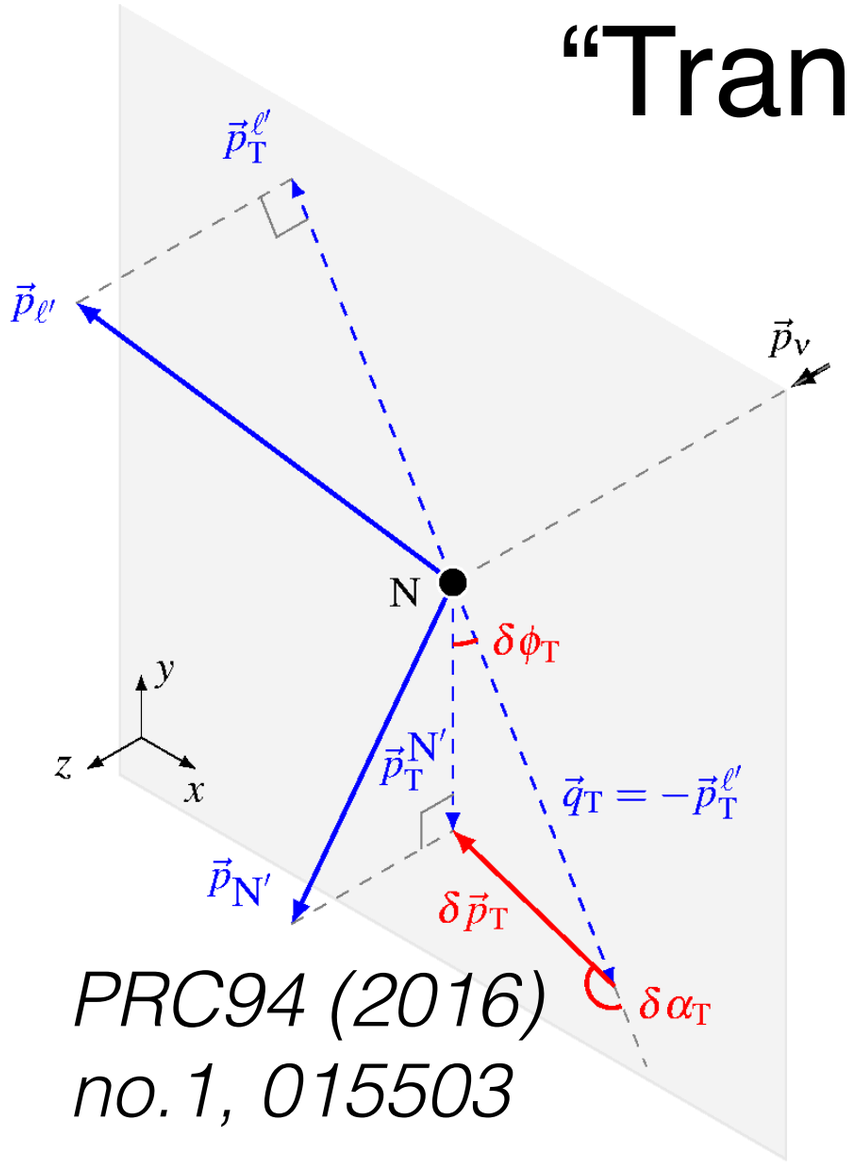
“Transverse variables”



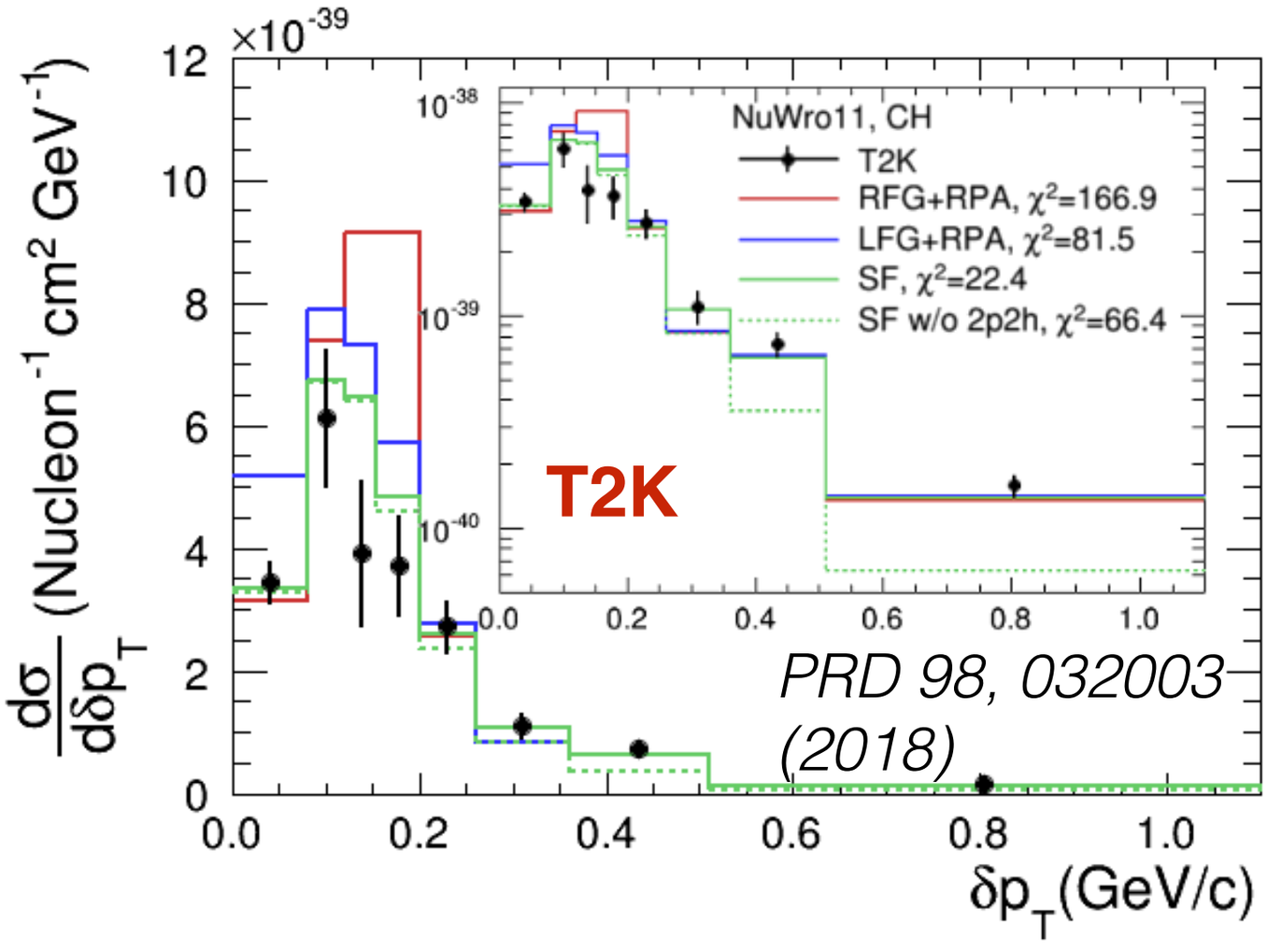
PRC94 (2016) no.1, 015503

- **New window (hadronic state) on neutrino interactions:** Kinematic variables relative to the beam direction are sensitive to nuclear effects.

“Transverse variables”



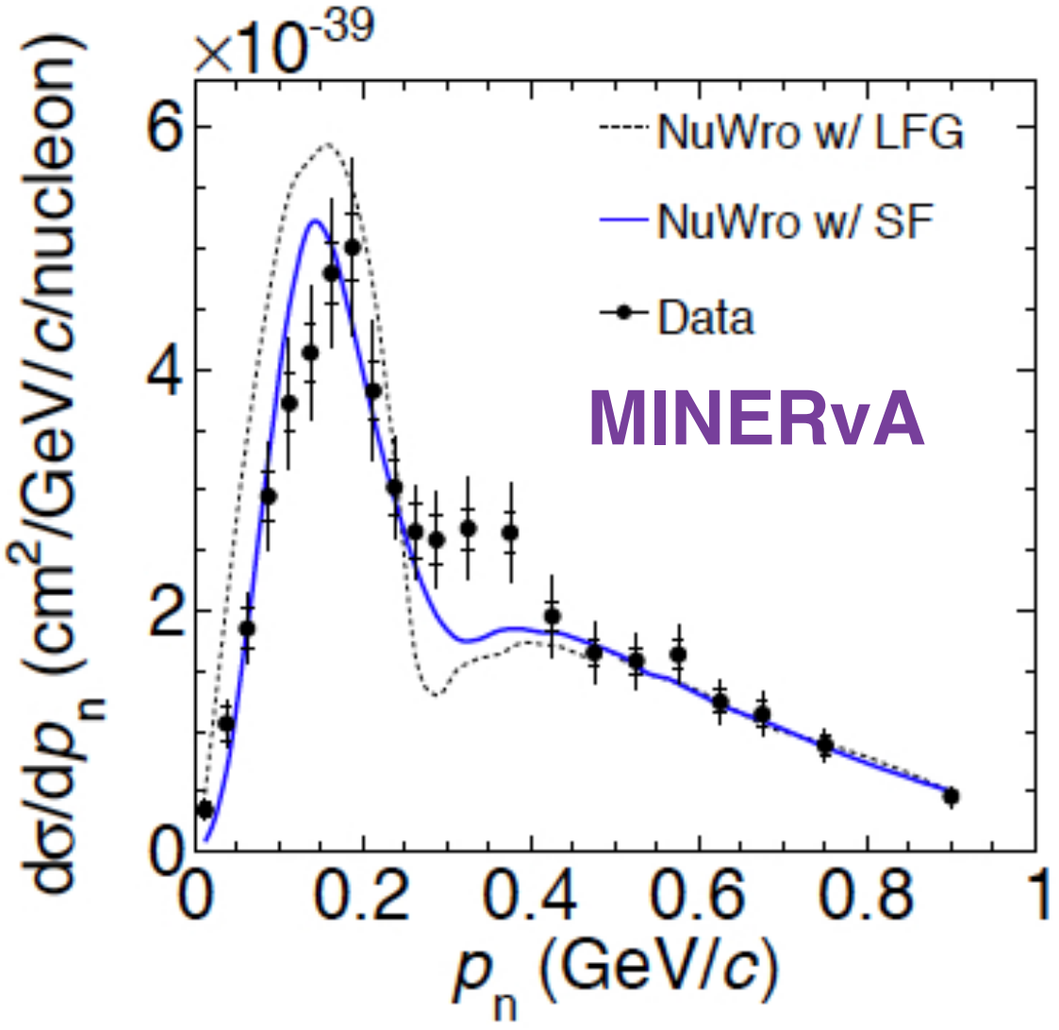
PRC94 (2016) no.1, 015503



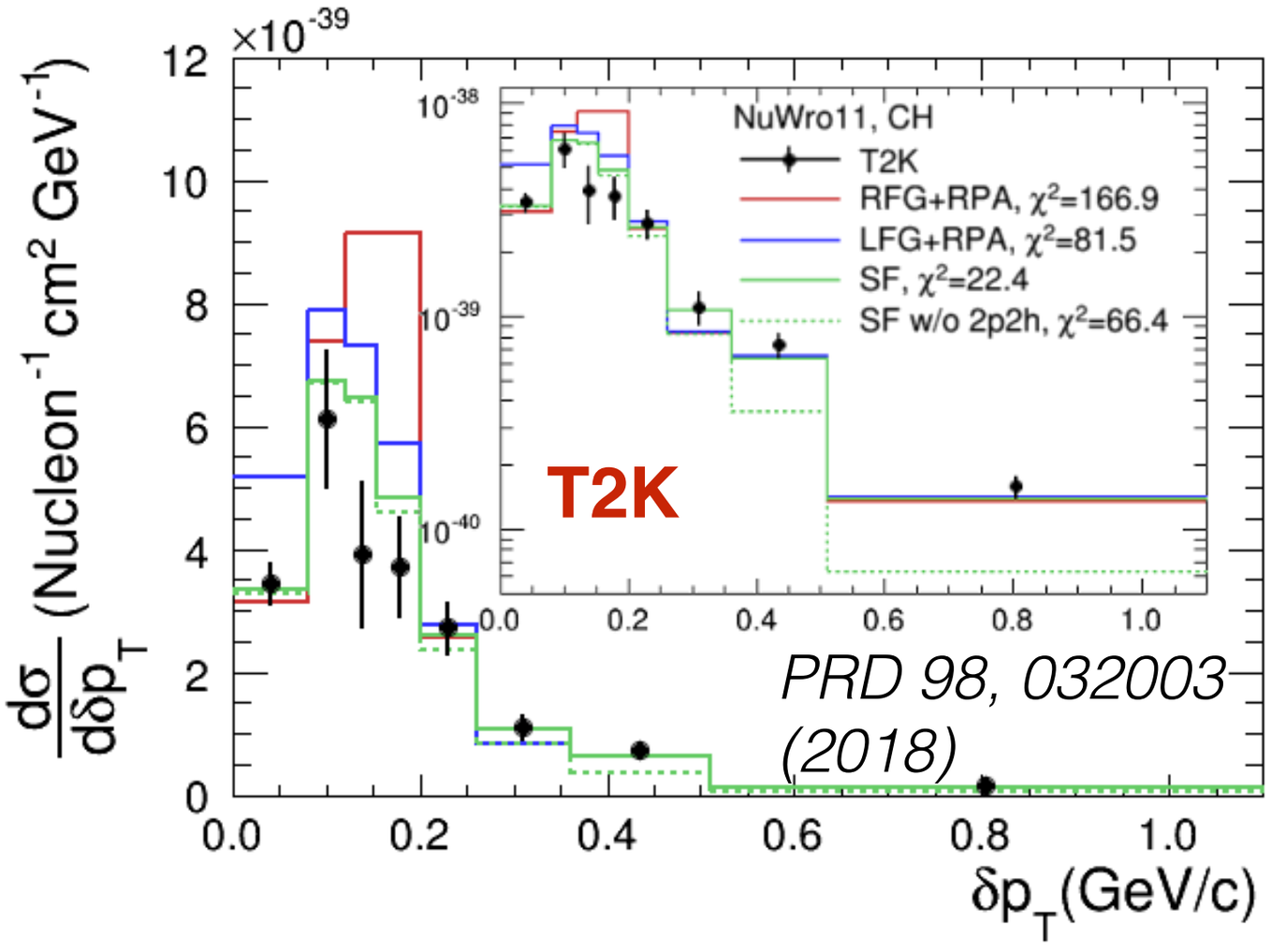
- **New window (hadronic state) on neutrino interactions:** Kinematic variables relative to the beam direction are sensitive to nuclear effects.

- Semi inclusive scattering of protons out of CCQE-like interactions;”0π+p”

“Transverse variables”



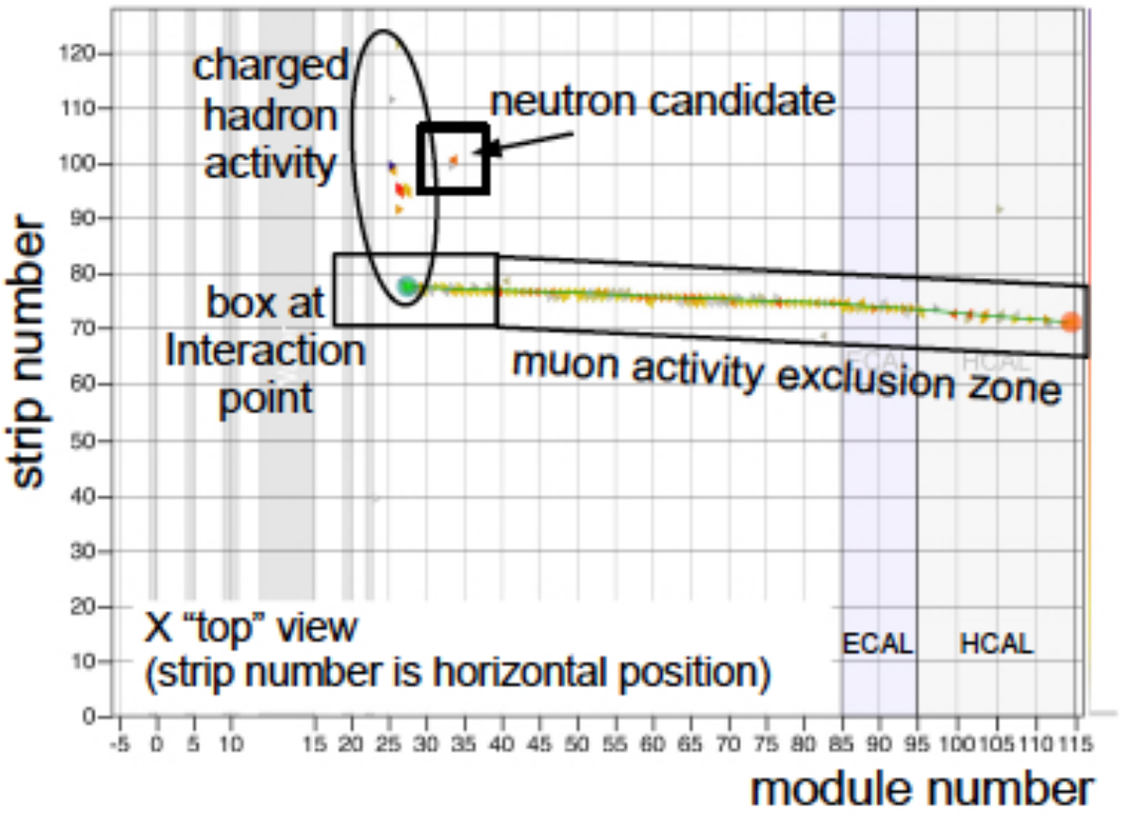
PRL 121, 022504 (2018)



PRD 98, 032003 (2018)

- New probes of nuclear model— multiple projections available
- Interpretation caveat: Simulations are using inclusive calculations (quasielastic plus 2p2h plus pion production) with a fragmentation model, plus an FSI cascade or transport. - *not full semi-inclusive theory*

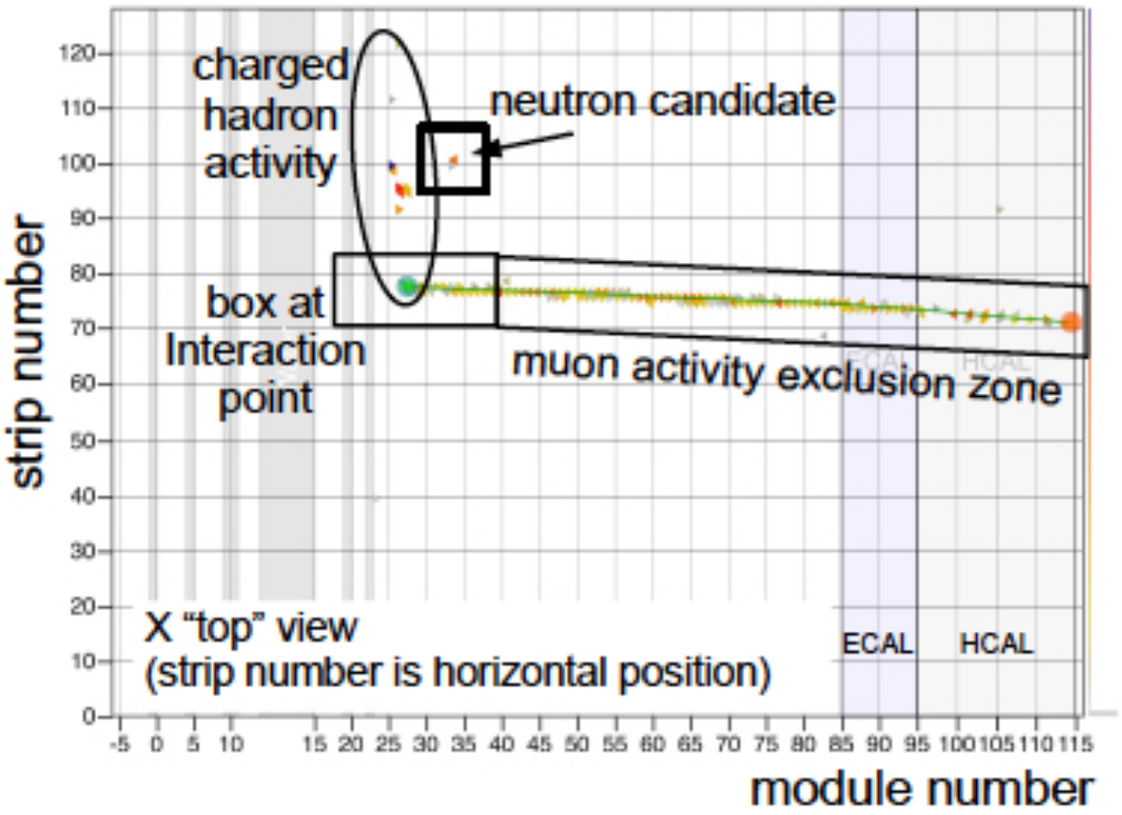
MINERvA: neutrons?!



arXiV:1901.04892, accepted by PRD

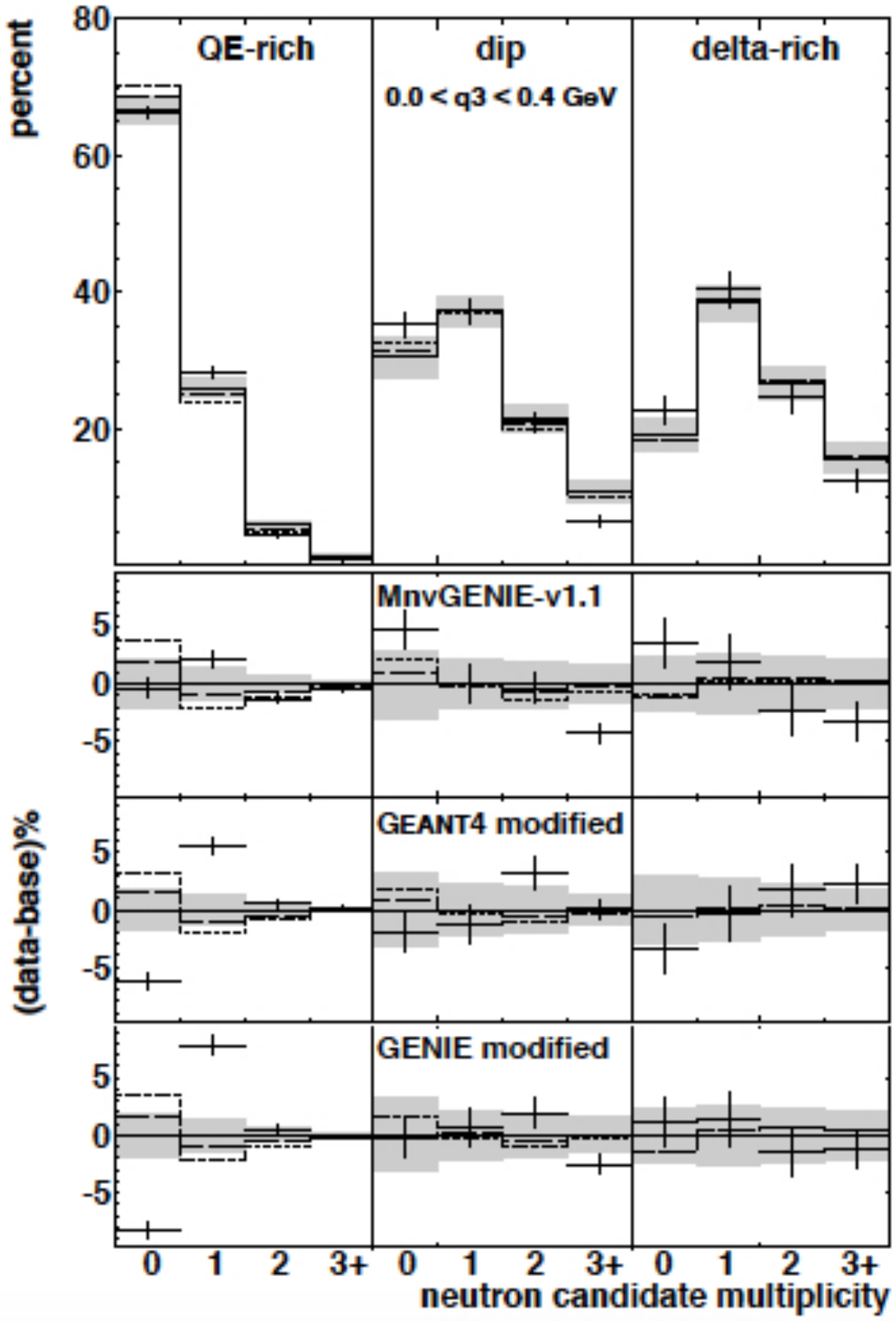
- Neutrons scatter off the H in the scintillator of the detector

MINERvA: neutrons?!

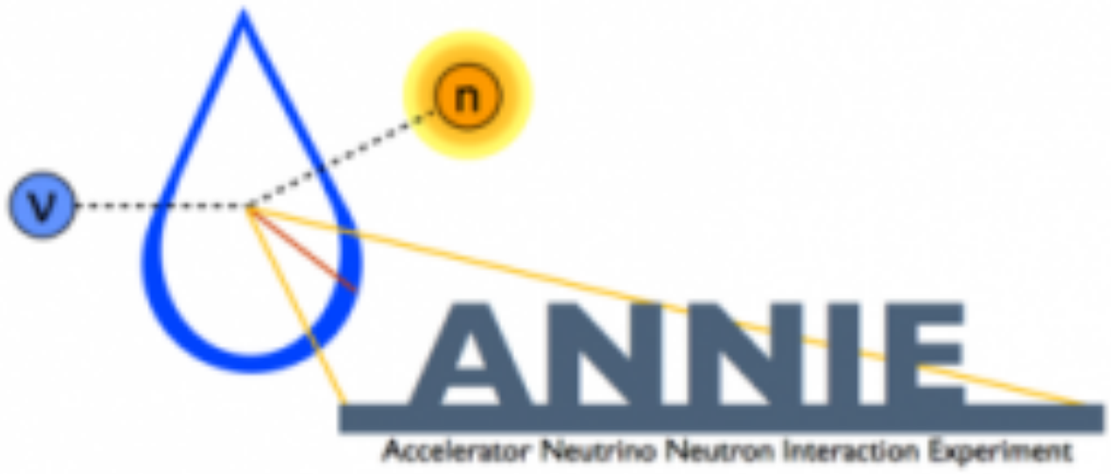


arXiV:1901.04892, accepted by PRD

- Neutrons scatter off the H in the scintillator of the detector
- Comparison to earlier tune, and modifications to GEANT4 transport



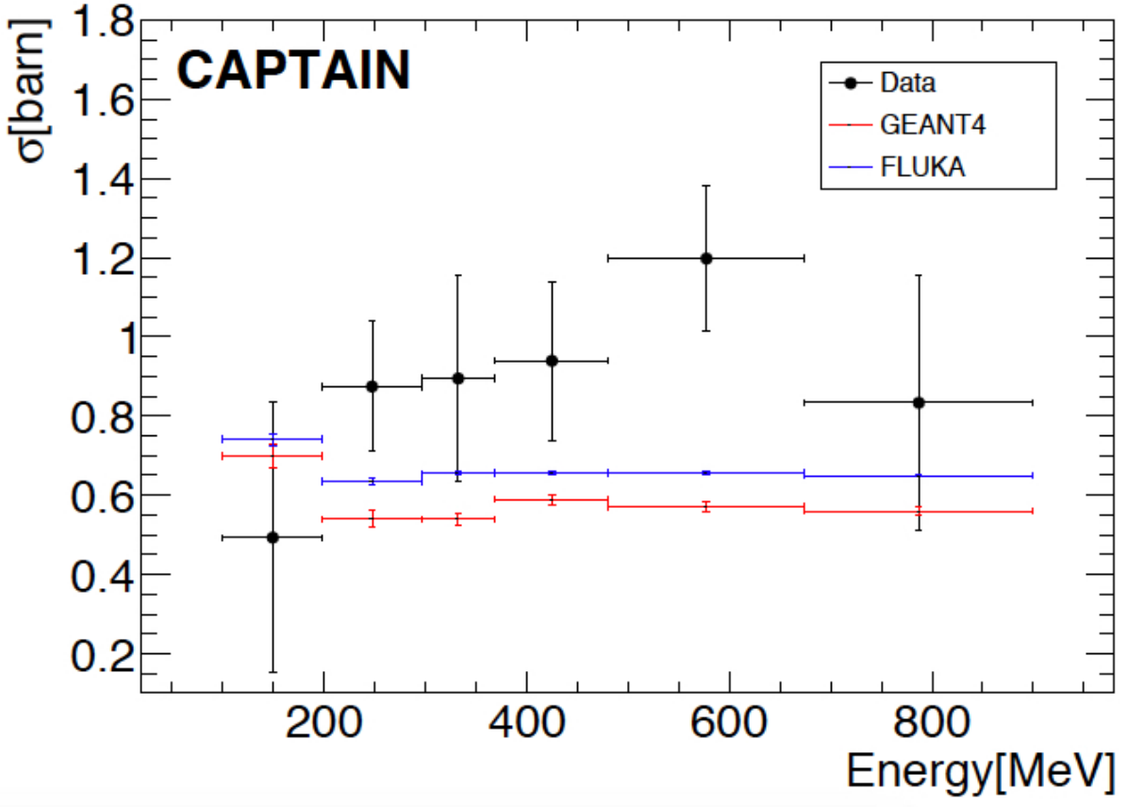
Other neutron measurements



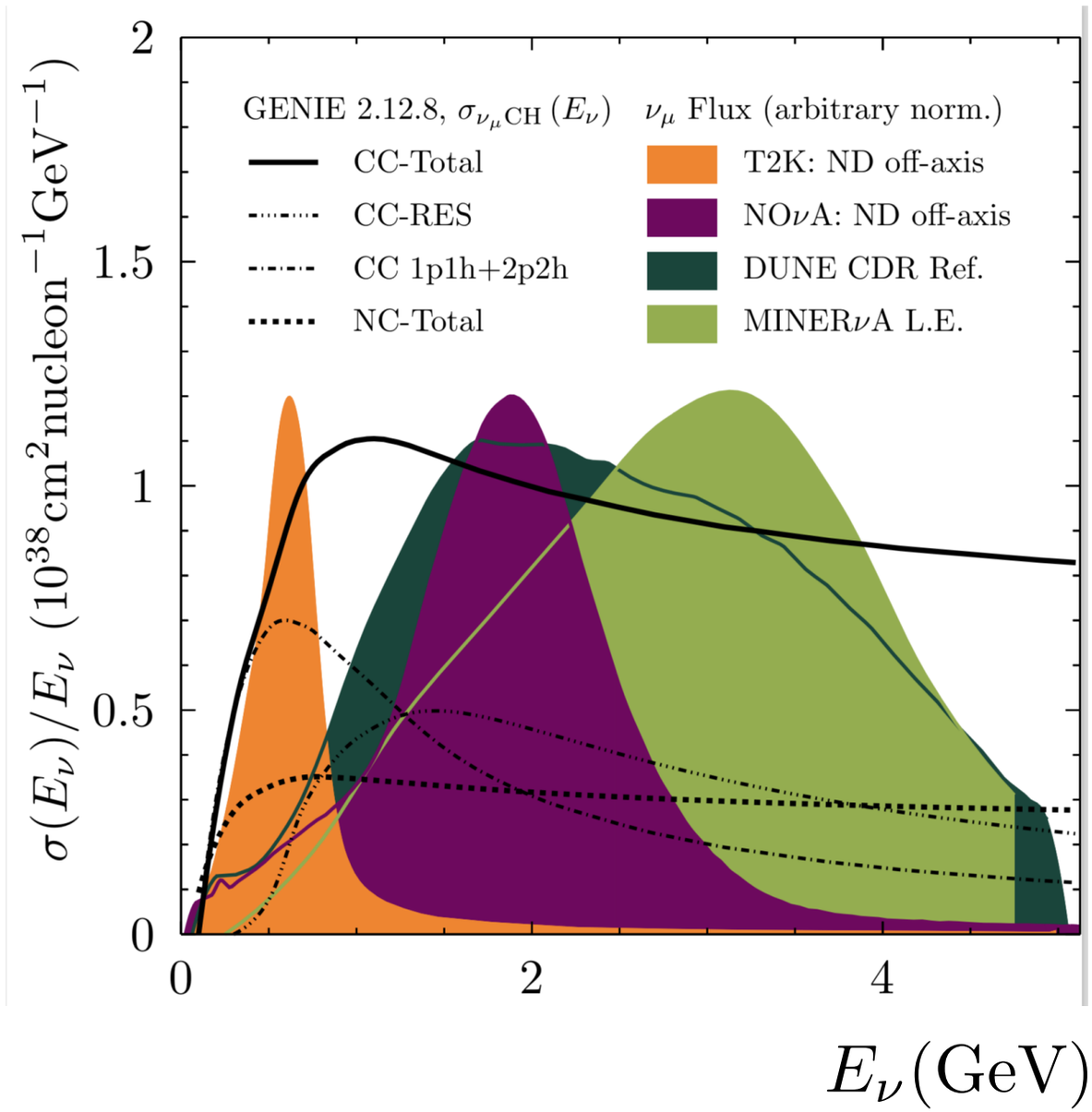
- Use fast timing detectors (LAPPD) to tag neutrons out of CC interactions

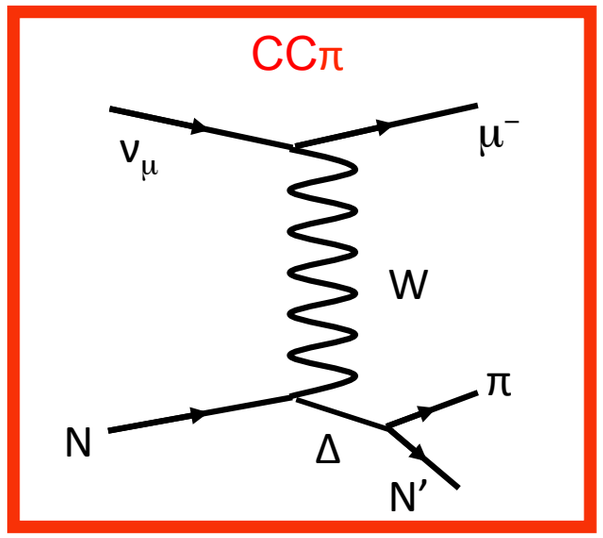
- Characterize neutron scatters in Argon

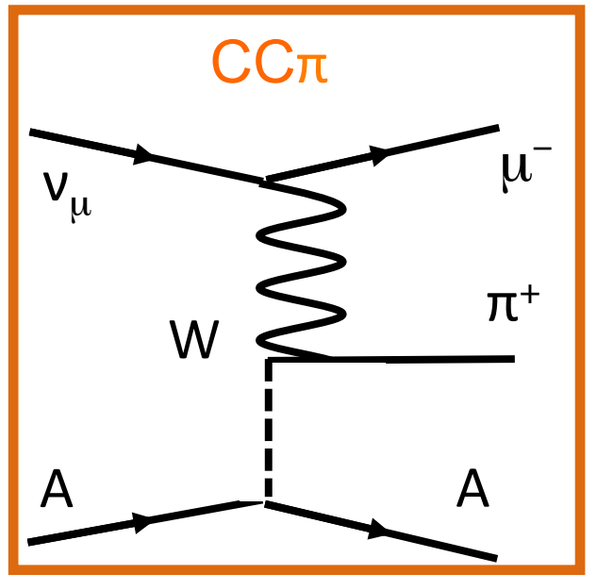
  Phys.Rev.Lett. 123 (2019) no.4, 042502



Important role of test beam information as well in cross section results







+ CC inclusive

+ NC

Single Pion Production Puzzles

- Important background (and signal) process for oscillation (non-standard) physics

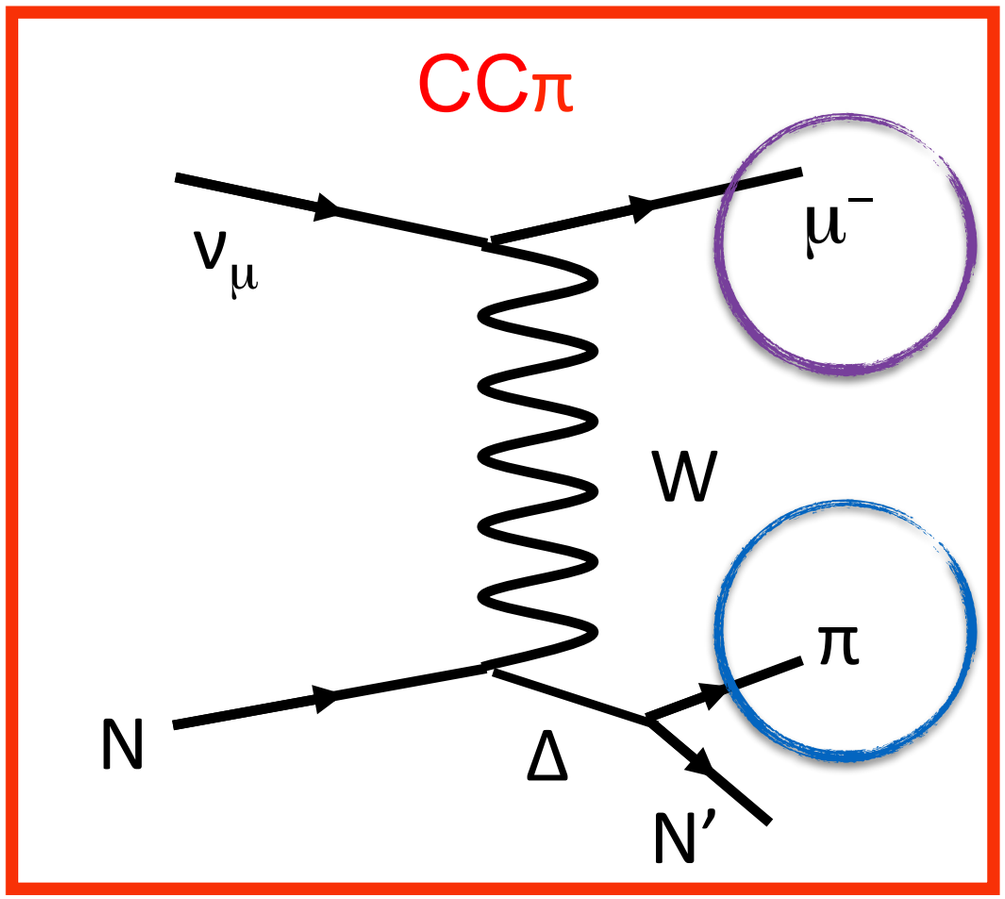
- **Challenge to model!**

  - non-resonant backgrounds?

  - pion re-interaction (final state interaction) model?

  - Busted single nucleon model?

- Example from NUISANCE software framework thanks to C. Wilkinson - *Dec 2016 seminar:* http://npc.fnal.gov/neutrino-seminar-series/2016-2017-season/

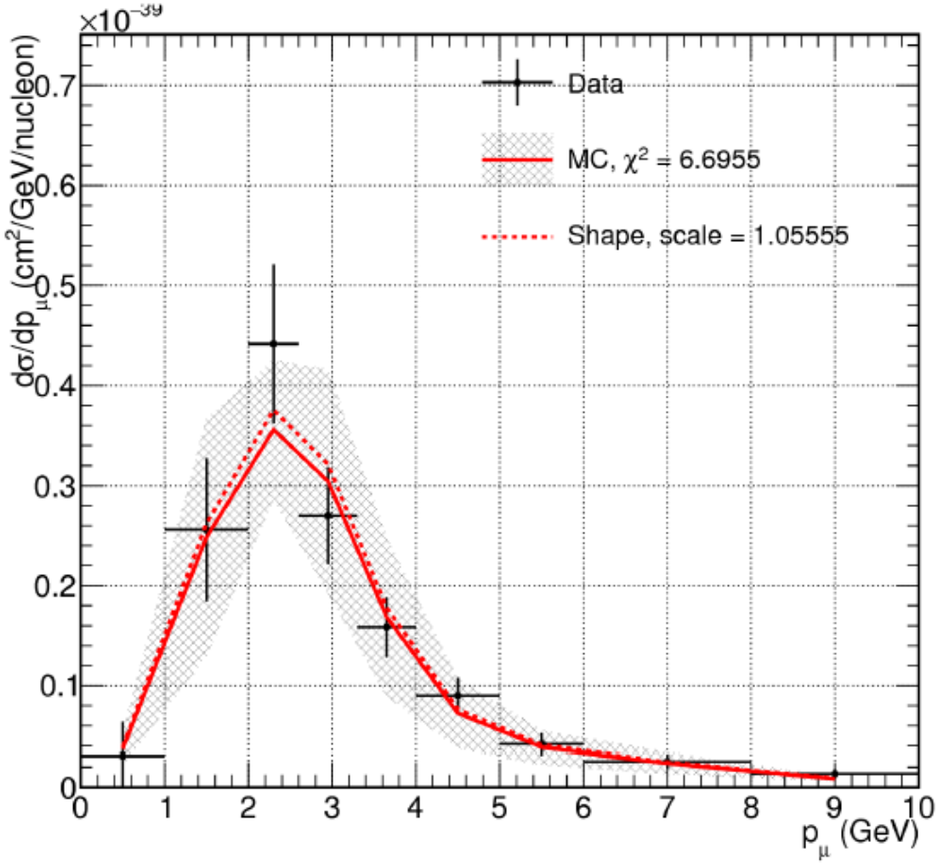


Single Pion Production Puzzles

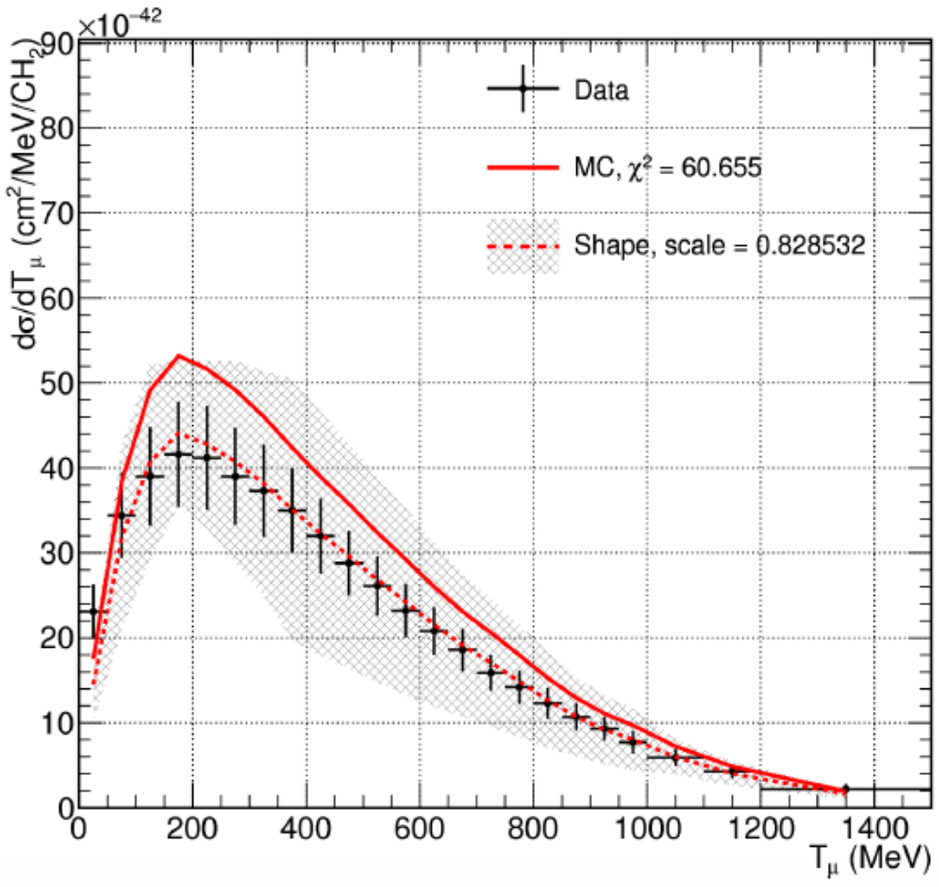
- **Reasonable agreement in outgoing muon spectrum**

- Terrible agreement in outgoing pion spectrum

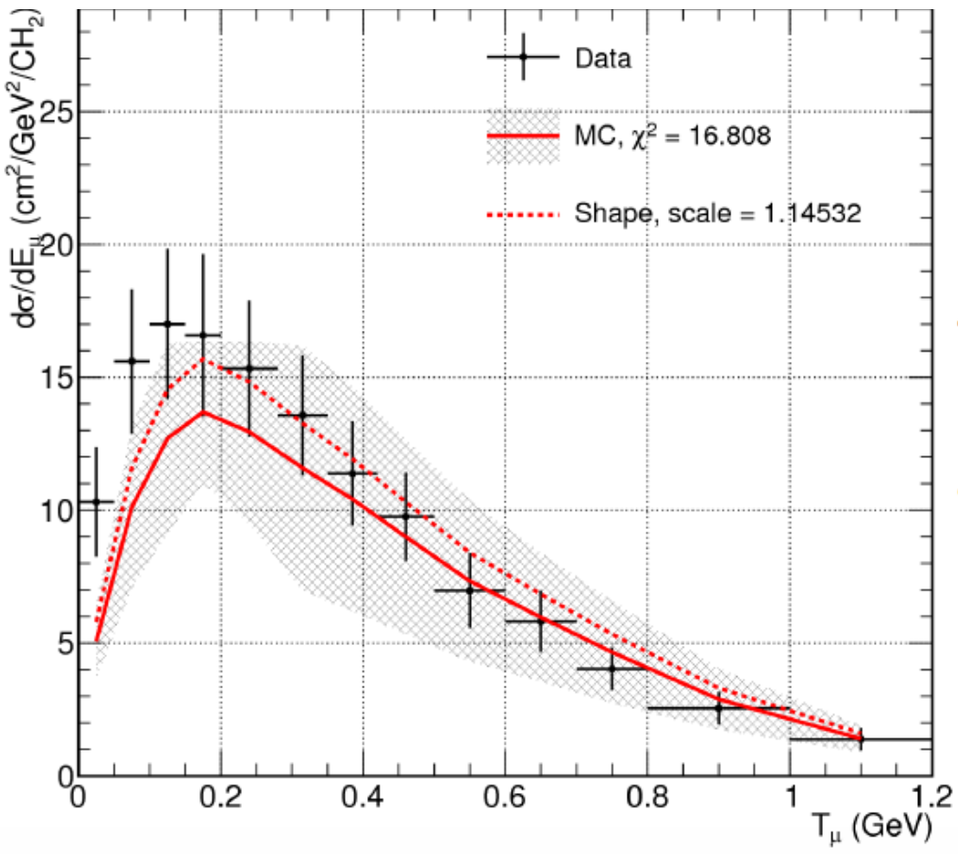
- Model development essential



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005



MB ν_μ-CH_2 CC1π^+
PRD 83 (2011) 052007



MB ν_μ-CH_2 CC1π^0
PRD 83 (2011) 052009

Single Pion Production Puzzles

- Reasonable agreement in outgoing muon spectrum
- **Terrible agreement in outgoing pion spectrum**
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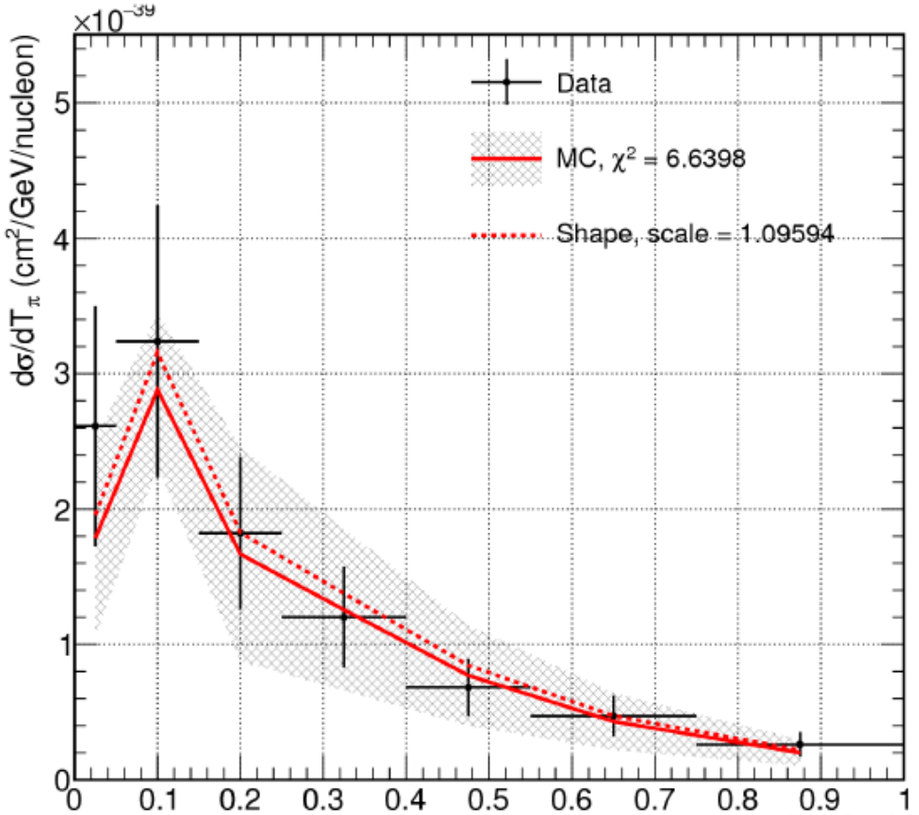
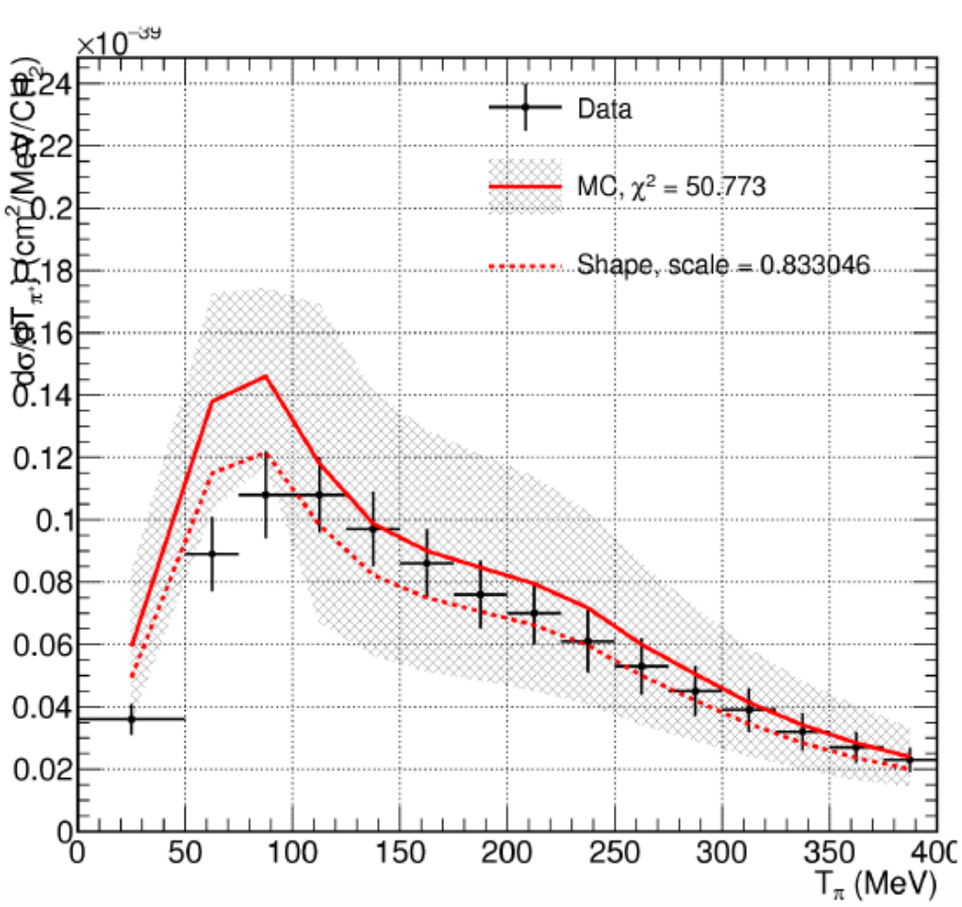
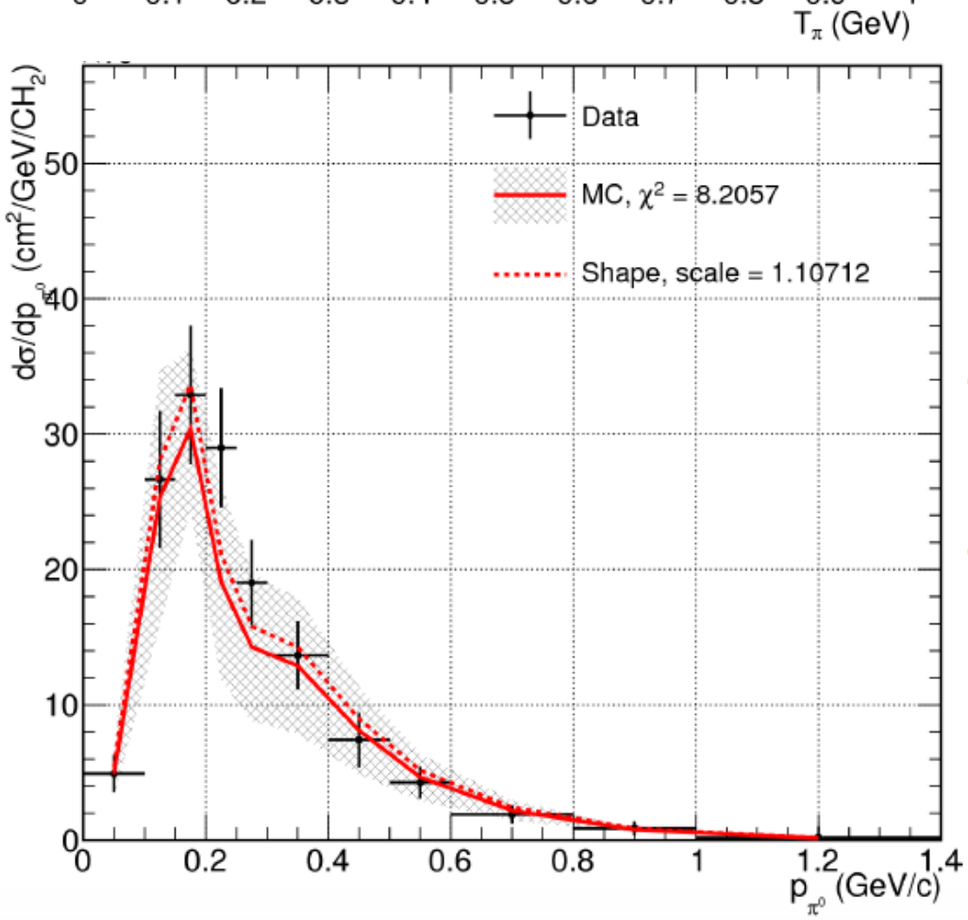


MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005



MB ν_μ-CH$_2$ CC1π^+
PRD 83 (2011) 052007



MB ν_μ-CH$_2$ CC1π^0
PRD 83 (2011) 052009

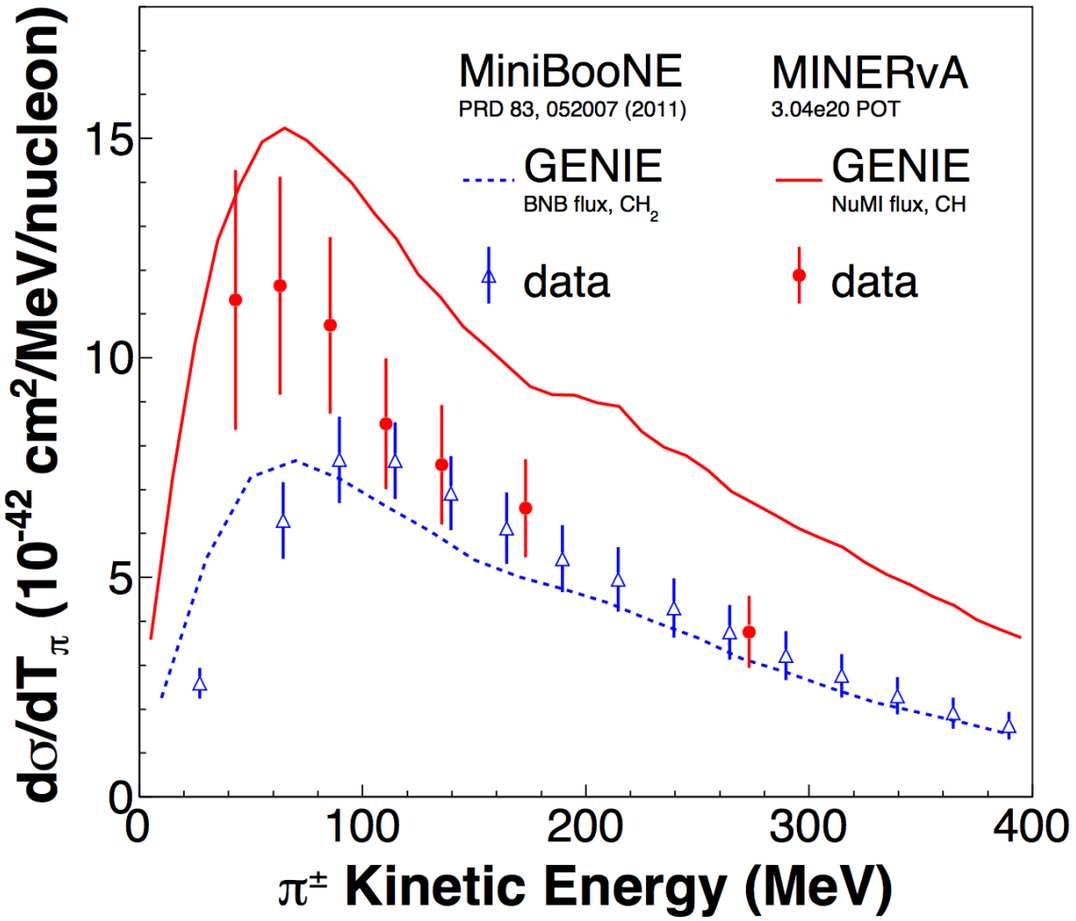
TENSIONS2016 Workshop idea

Inability to reconcile MiniBooNE, MINERvA QE-like, and single pion measurements within a single model ("data tensions")

- T2K attempts to fit [QE: PRD93 no. 7, 072010 (2016)]

- Summaries also at NuTUNE: https://indico.fnal.gov/conferenceDisplay.py?confId=11610]

- MINERvA comparisons to MiniBooNE [PRD92, 092008 (2015)]



TENSIONS2016 Workshop idea

Modern experiments, what's going on?

- Signal definition? Selection? Extraction?
- Hidden model dependance?
- Background subtraction? Control sample selection?
- Flux?

Group of experimentalists from three collaborations (MiniBooNE, MINERvA and T2K) came together to discuss.

Summary in Phys.Rept. 773-774 (2018) 1-28

QE-like Signal, Background Definitions

What signal definition is used by each experiment?

- MiniBooNE: CC0π and CCQE (NUANCE)
- MINERvA: CCQE* (GENIE) before FSI
- T2K: CC0π (NEUT)

Tensions: Different signal/background definitions

- Can we compare MiniBooNE to MINERvA CCQE?
  - No. MiniBooNE CCQE = CC with no final state pions - CC with pion absorbed. -> *Movement to final state topology definitions*
- Caveat: detector response in MiniBooNE is similar for 2p2h and QE and pion absorbed. Not true for MINERvA.

QE-like Signal, Background Definitions

What signal definition is used by [illegible] experiment?

- MiniBooNE: CC0π and
- [illegible]
- T2K: C

Tensions: Diffe[illegible]

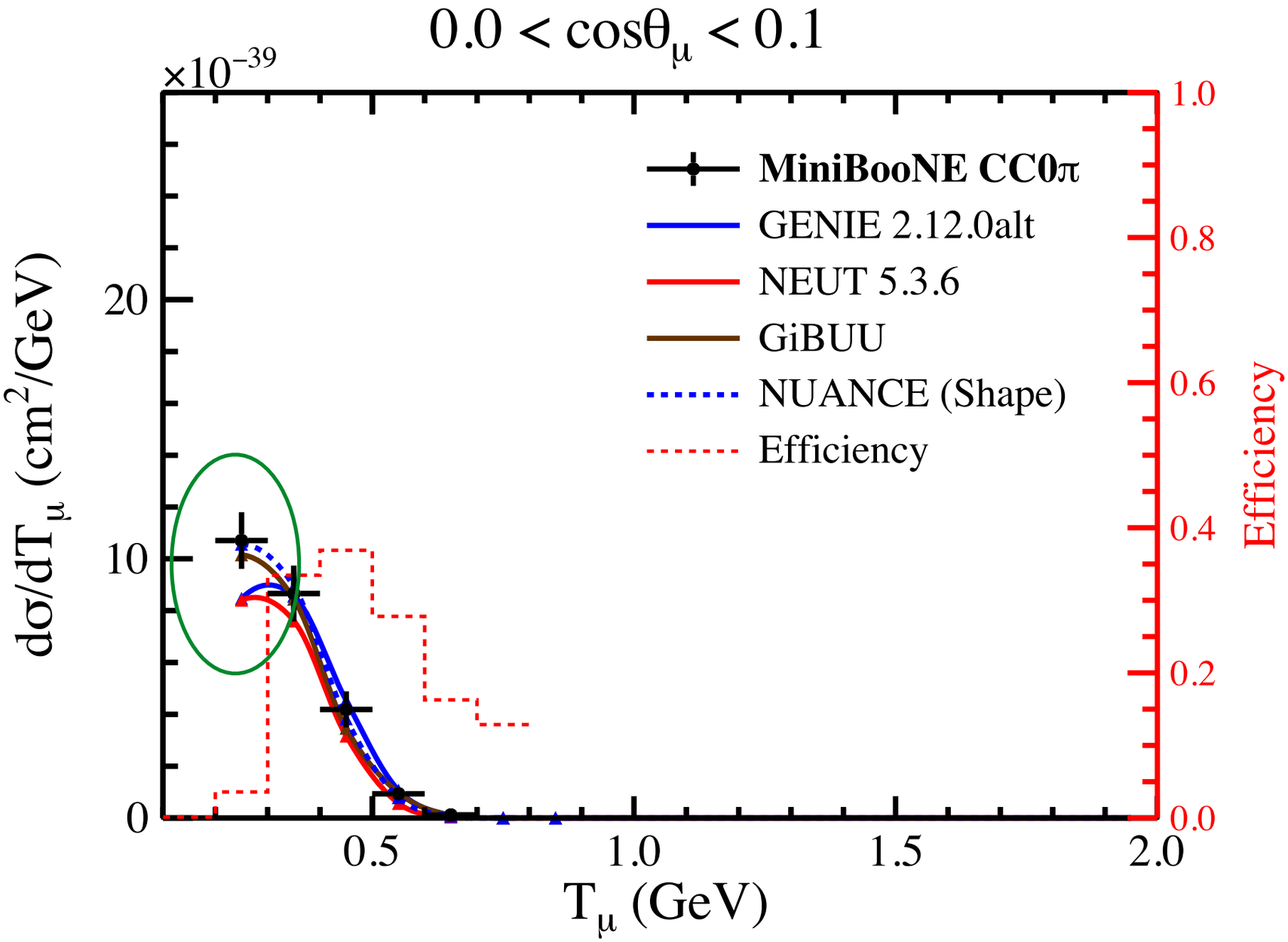
- Can we compa[illegible]
  - No. MiniBooNE CCQE = CC with no final state pions + CC with pion absorbed. -> *Movement to final state topology definitions*
- Caveat: detector response in MiniBooNE is similar for 2p2h and QE and pion absorbed. Not true for MINERvA.

Similar issues in single pion comparisons.

Complicated by use in selections of true quantities (analysis-specific, difficult for user to interpret)

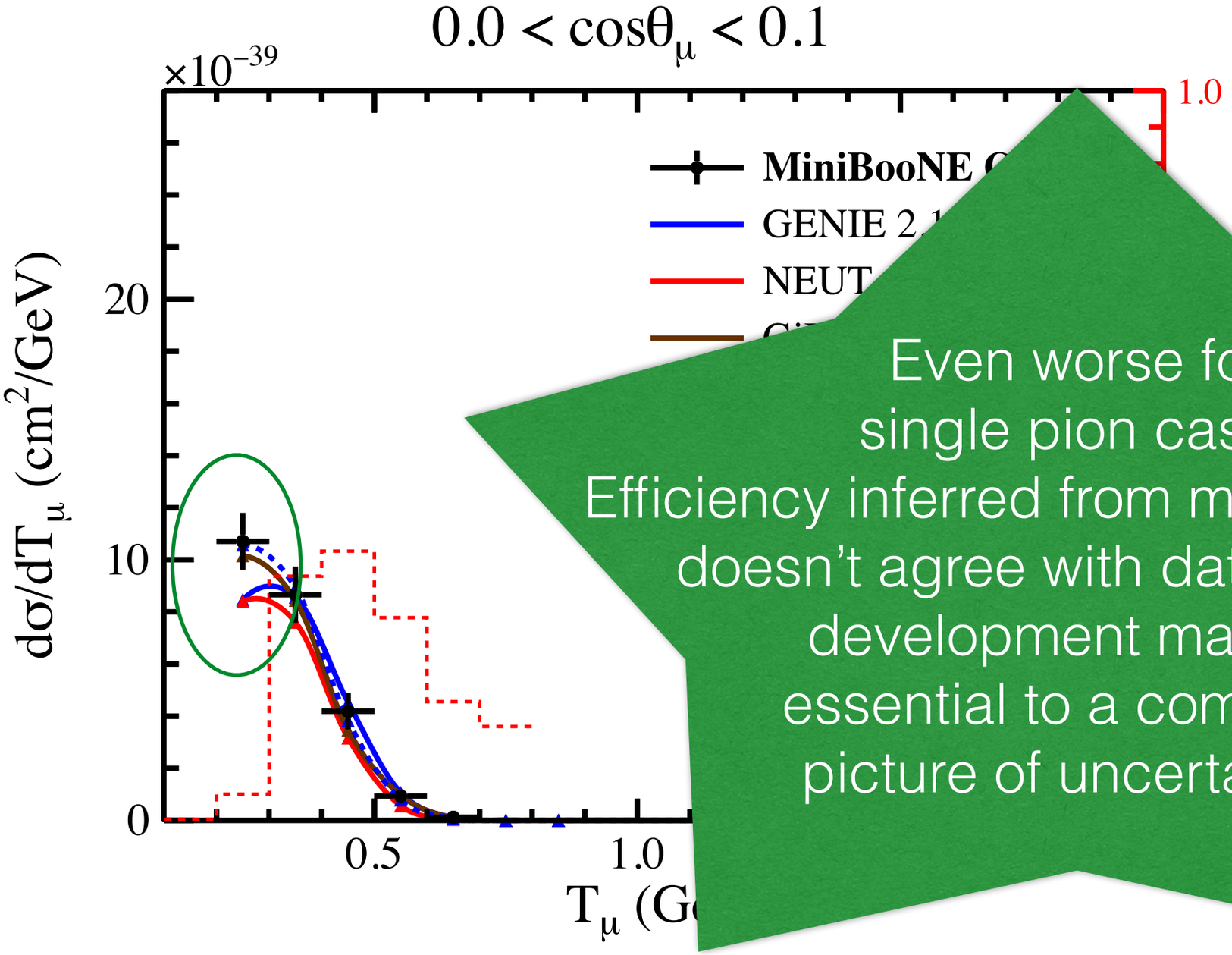
Small but noticeable backgrounds sometimes difficult to identify in signal definition as provided.

Thoughts on efficiency



Where efficiency changes rapidly, or is very low, may be more susceptible to choice of model used in analysis

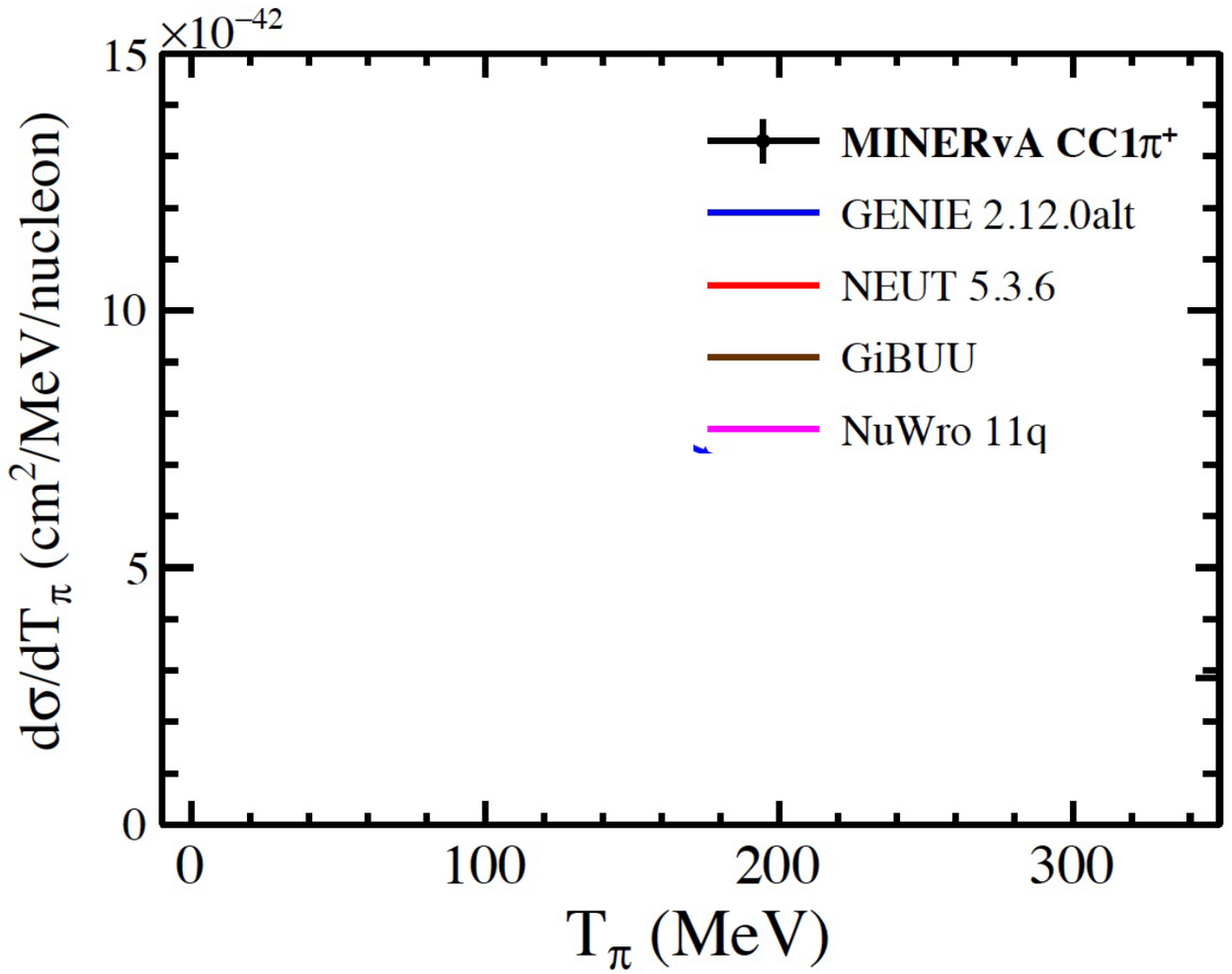
Thoughts on efficiency

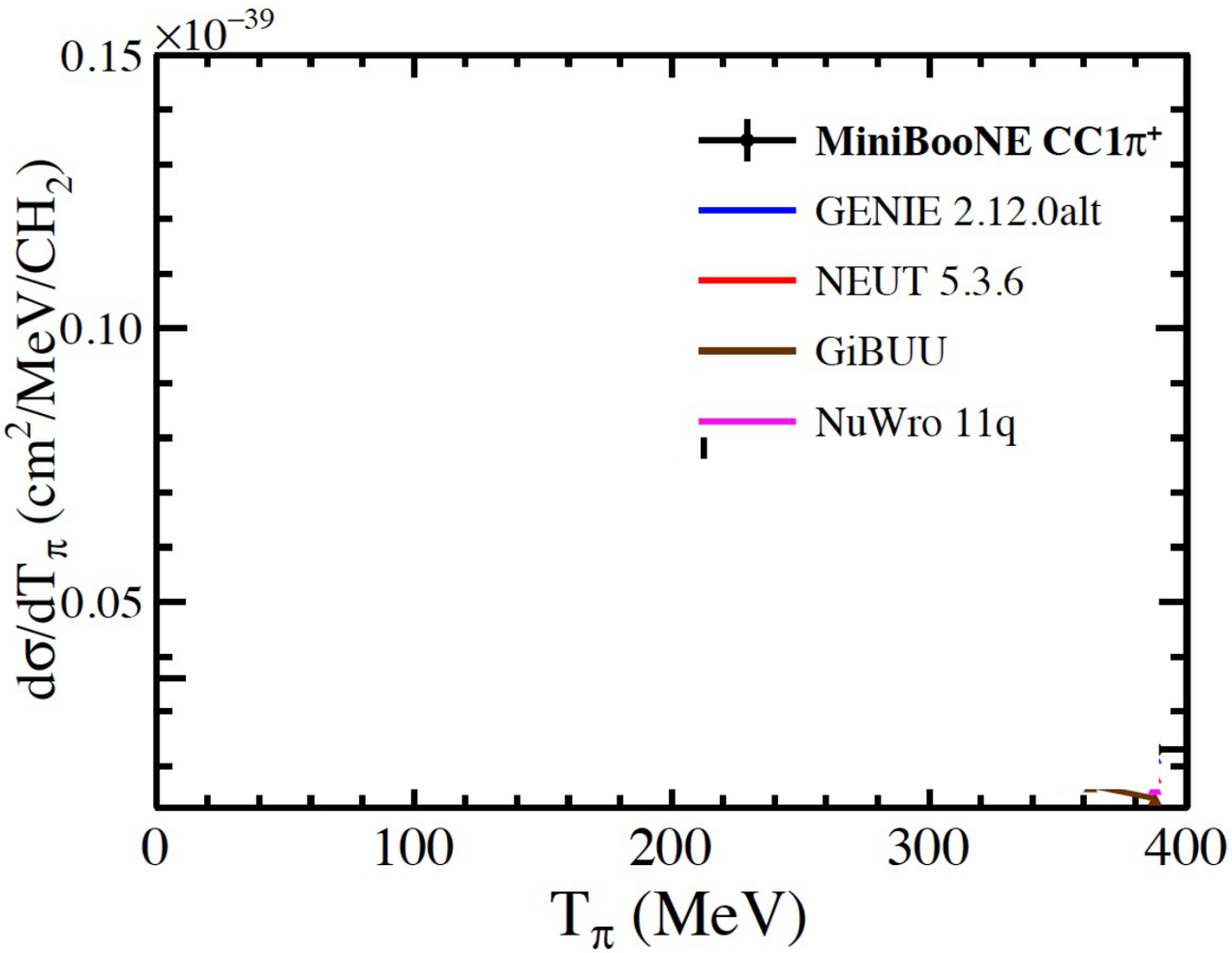


Even worse for single pion case!
Efficiency inferred from model… which doesn't agree with data. Model development may be essential to a complete picture of uncertainty.

Where efficiency changes rapidly, or is very low, may be more susceptible to choice of model used in analysis

Tensions revisited: single pion production

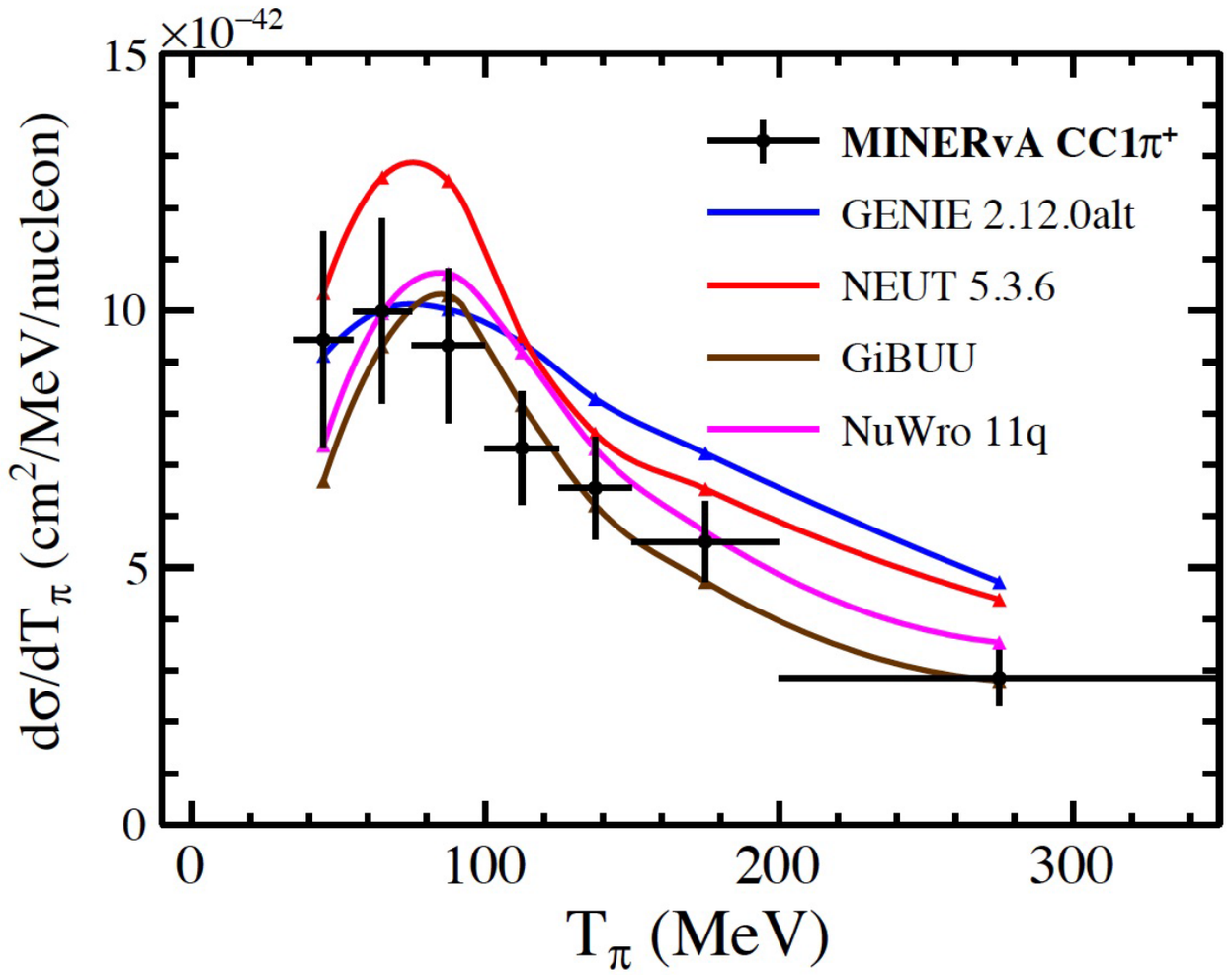




Same models, correct signal definition, proper flux averaging

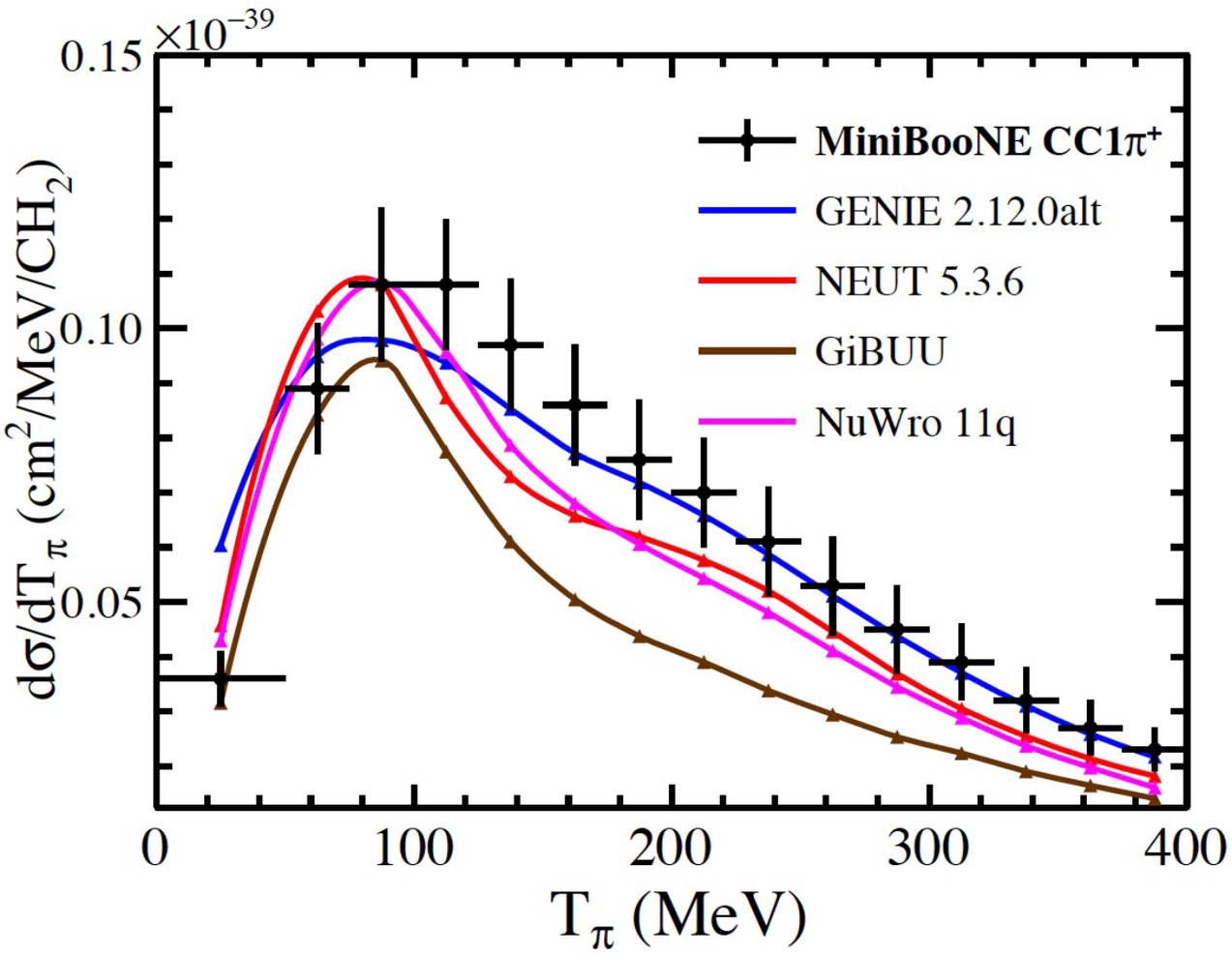
Prepared with NUISANCE

Tensions revisited: single pion production



Updated flux prediction from MINERvA!

Roughly, better normalization agreement now



But still, shape discrepancies remain

Updated fit to all MINERvA data: arXiv:1903.01558

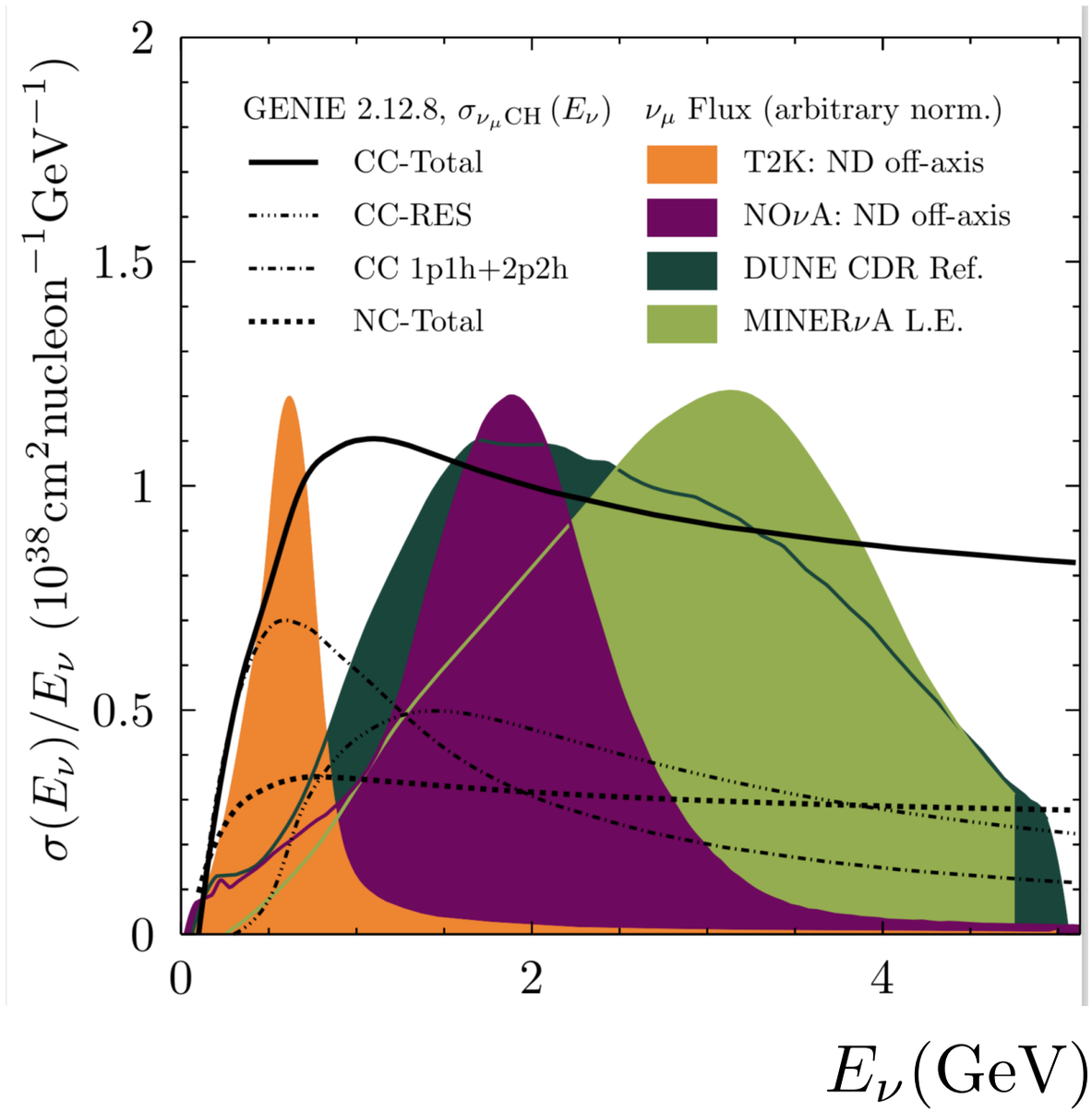
An aside: What do we mean by “agreement”?

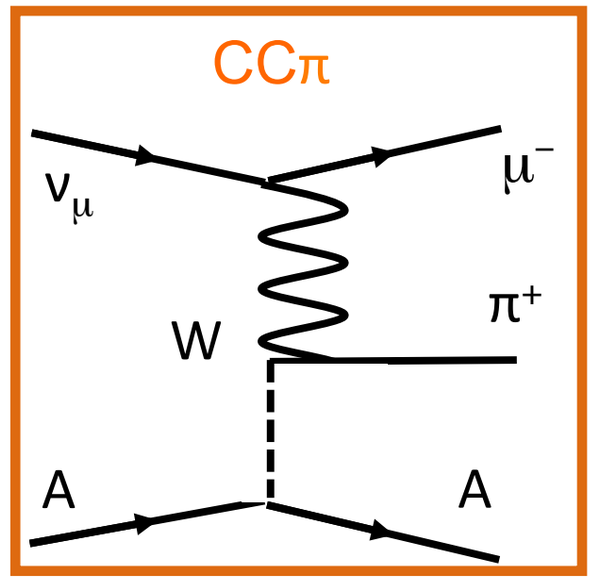
- “Chi-by-eye” lacks inclusion of correlations, which may affect conclusions
  - Frequently, measurements have strong bin-bin correlations
- One projection may shows agreement, others may not.
- Our models may also include implementation assumptions
  - What a generator calls semi-inclusive may not be a true semi-inclusive model

Open question for how to ‘complete the circle’ Frequent use of internal closure tests: do we extract a known “true” cross section correctly?

Pieces of the Single Pion puzzles

- Still, major difficulties reconciling data
  - T2K, MINERvA are updating both base pion production models and their analyses to see if discrepancies can be resolved or reduced
- Next frontier: DUNE— SPP is one of the dominant channels!





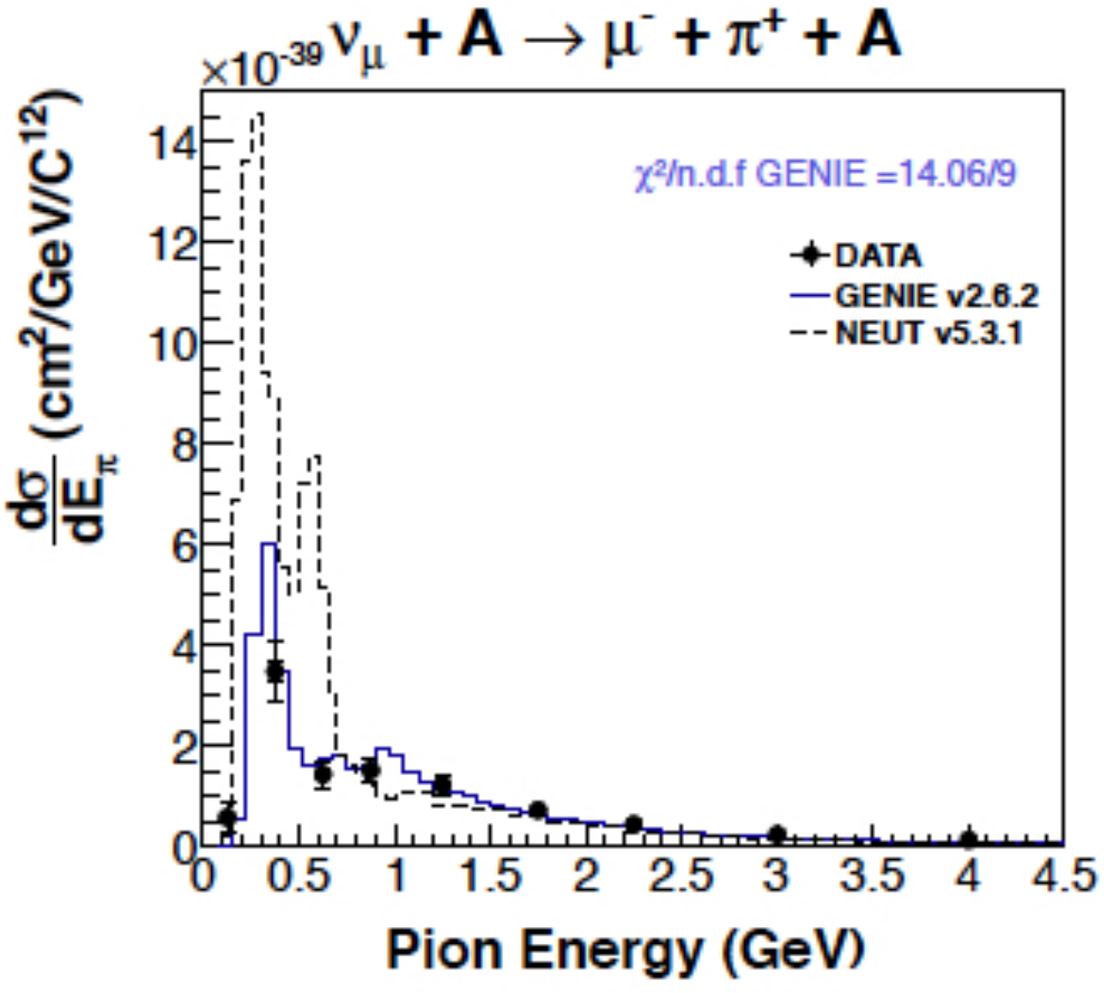
+ CC inclusive

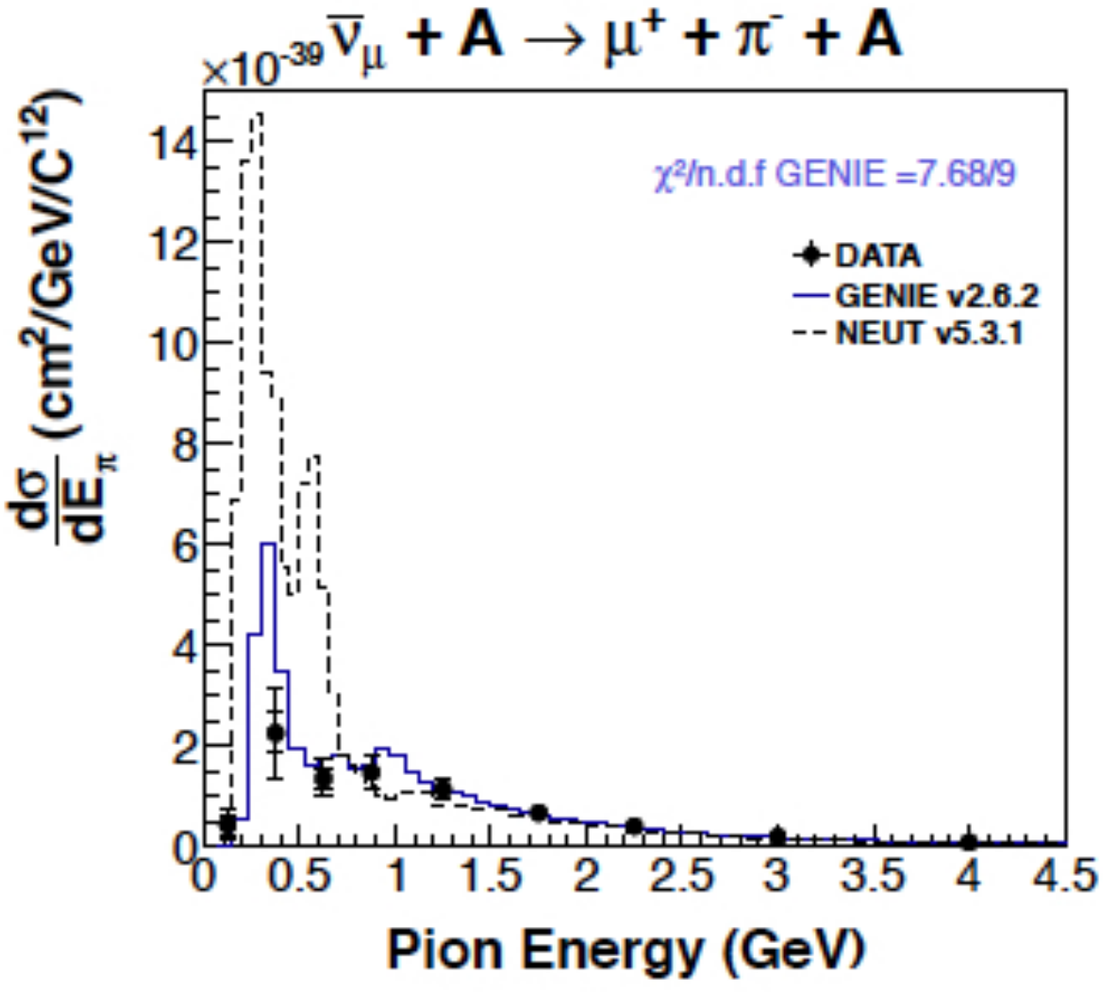
+ NC

Coherent Pion Production

- **Observation of coherent v-C scattering from MINERvA** [*Phys. Rev.Lett. 113, 261802 (2014).*]

Success! Detection and modeling of rare process



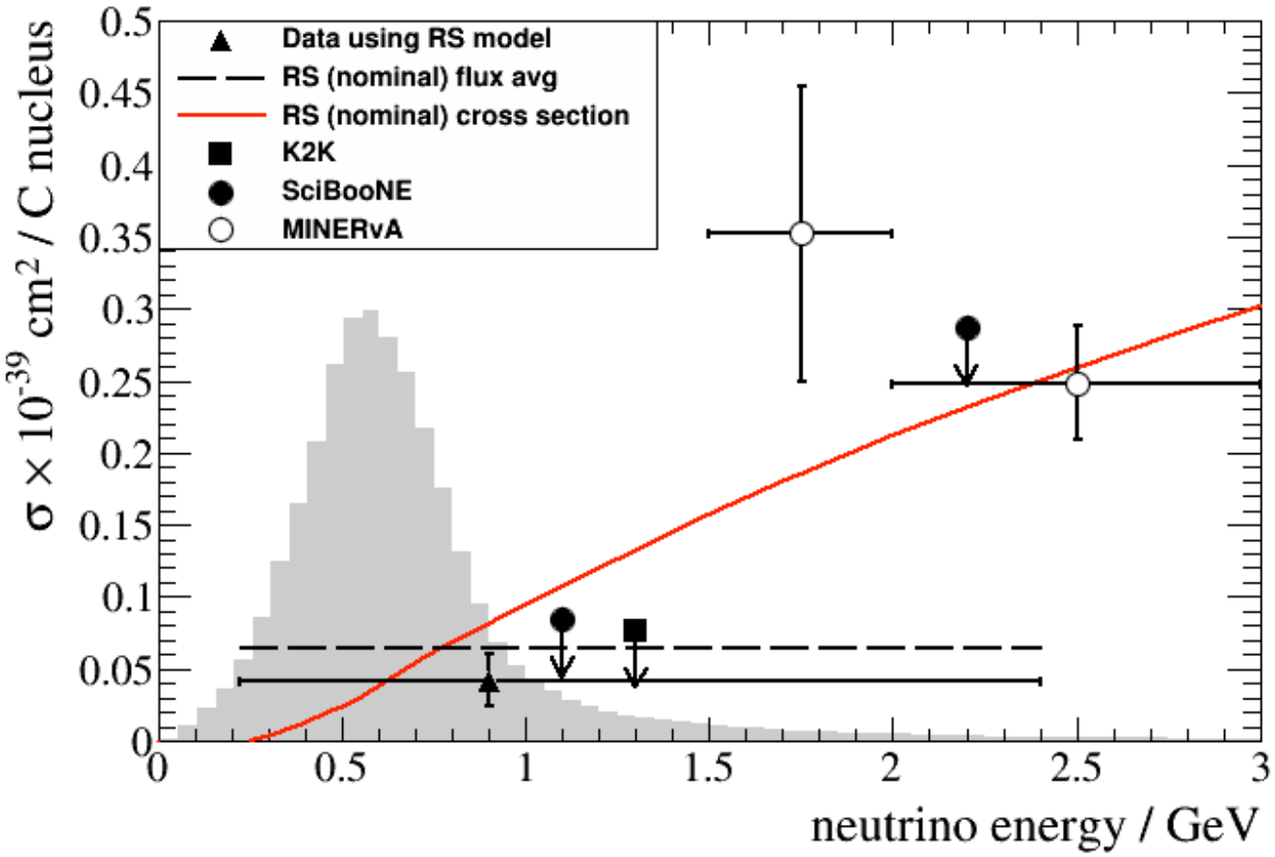


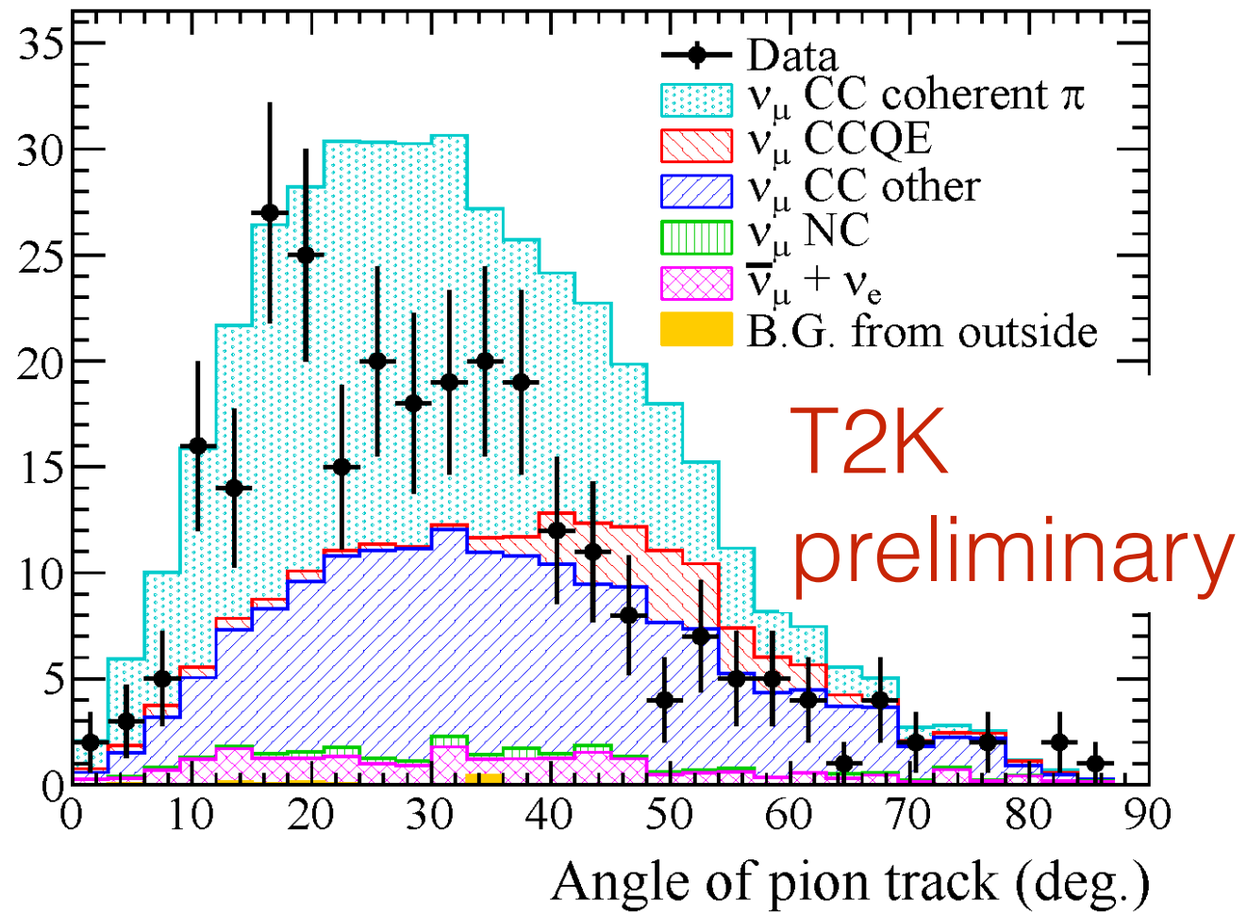
Coherent Pion Production

- **Observation of coherent v-C scattering from MINERvA**

- **T2K measurements** *Phys.Rev.Lett. 117 (2016) no.19, 192501*

S. Cao, NuInt2015

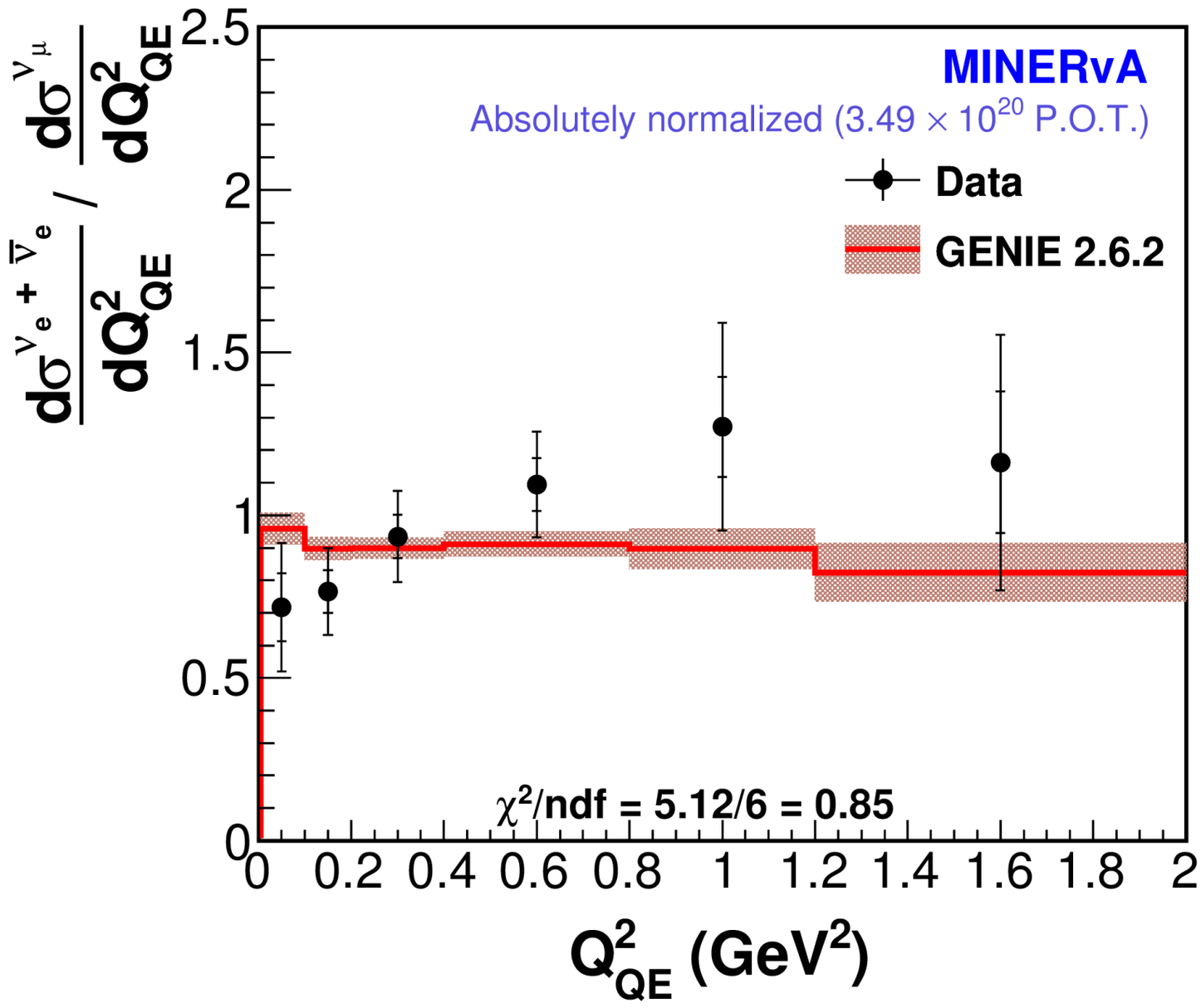




off-axis: 2.2σ excess over background, consistent with and lower than current models

on-axis: 1.7σ excess over background, suppression at high pion angle like MINERvA

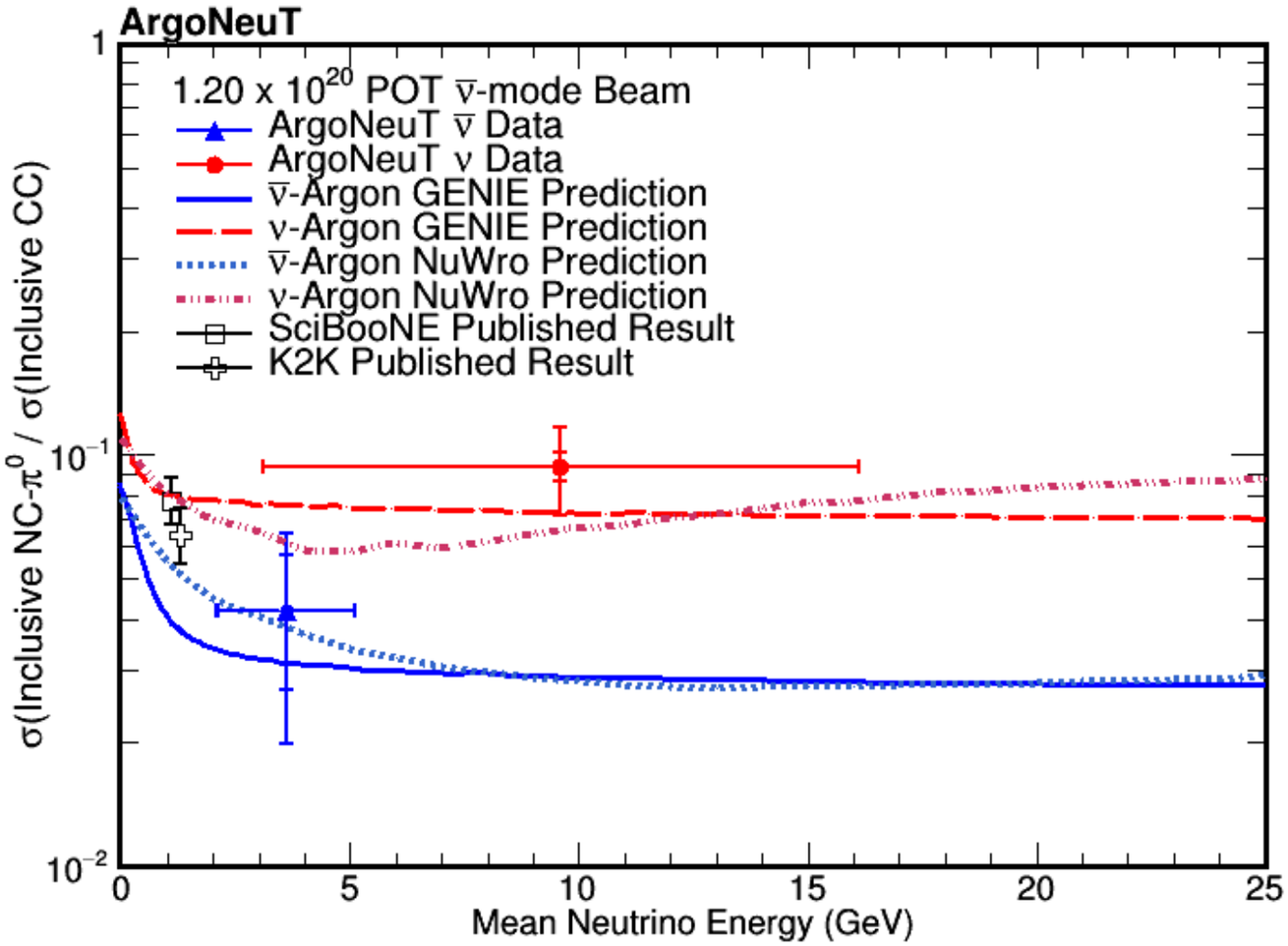
Electron Neutrino Interactions

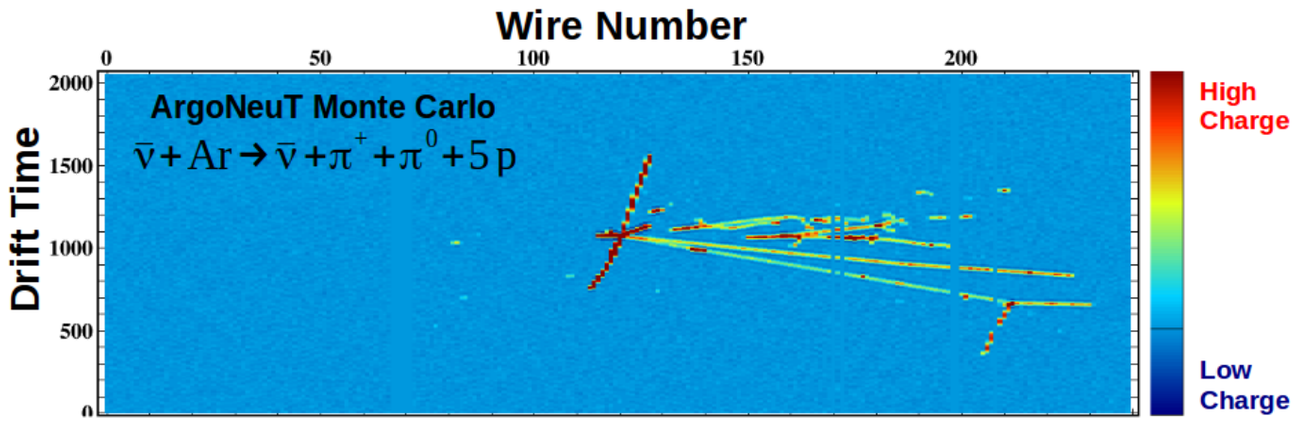


- Measurement from MINERvA [*Phys. Rev. Lett 116, 081802*]:
  Sets scale of different ν_e/ν_μ nuclear effects of <15-30%

- T2K measurement: *Phys.Rev.Lett. 113 (2014) no.24, 241803*

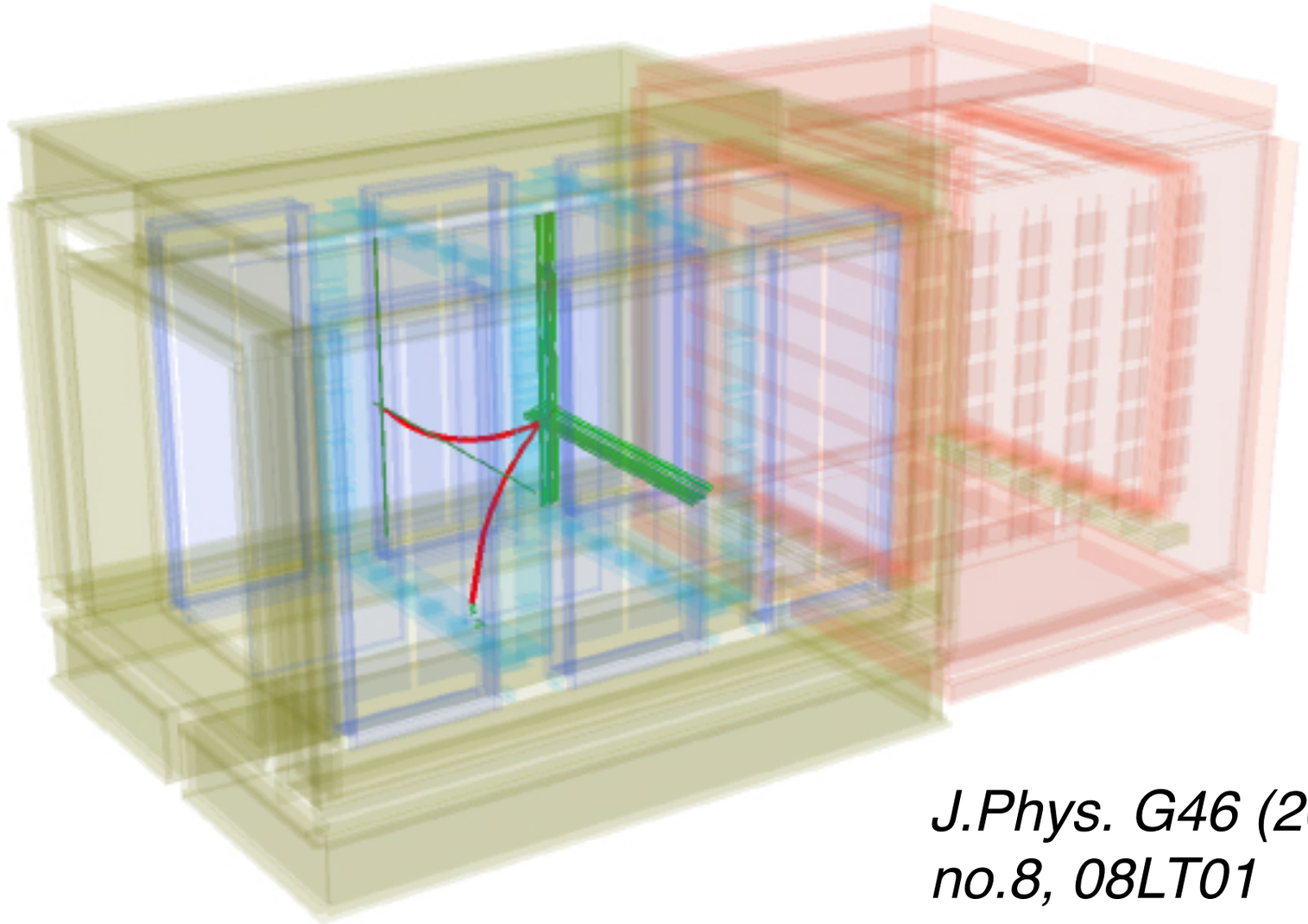
Neutral Current Measurements





- NCπ^0 is a background to ν_e appearance searches
  - Challenge to reconcile MiniBooNE NC and CC $\pi^{0/+}$ production within same model
- **Evidence for NC diffractive π^0 seen by MINERvA** [*Phys. Rev. Lett. 117, 111801]*
- **Proof-of-concept LAr NCπ^0 measurement from ArgoNeuT** [*Phys. Rev. D 96, 012006]*

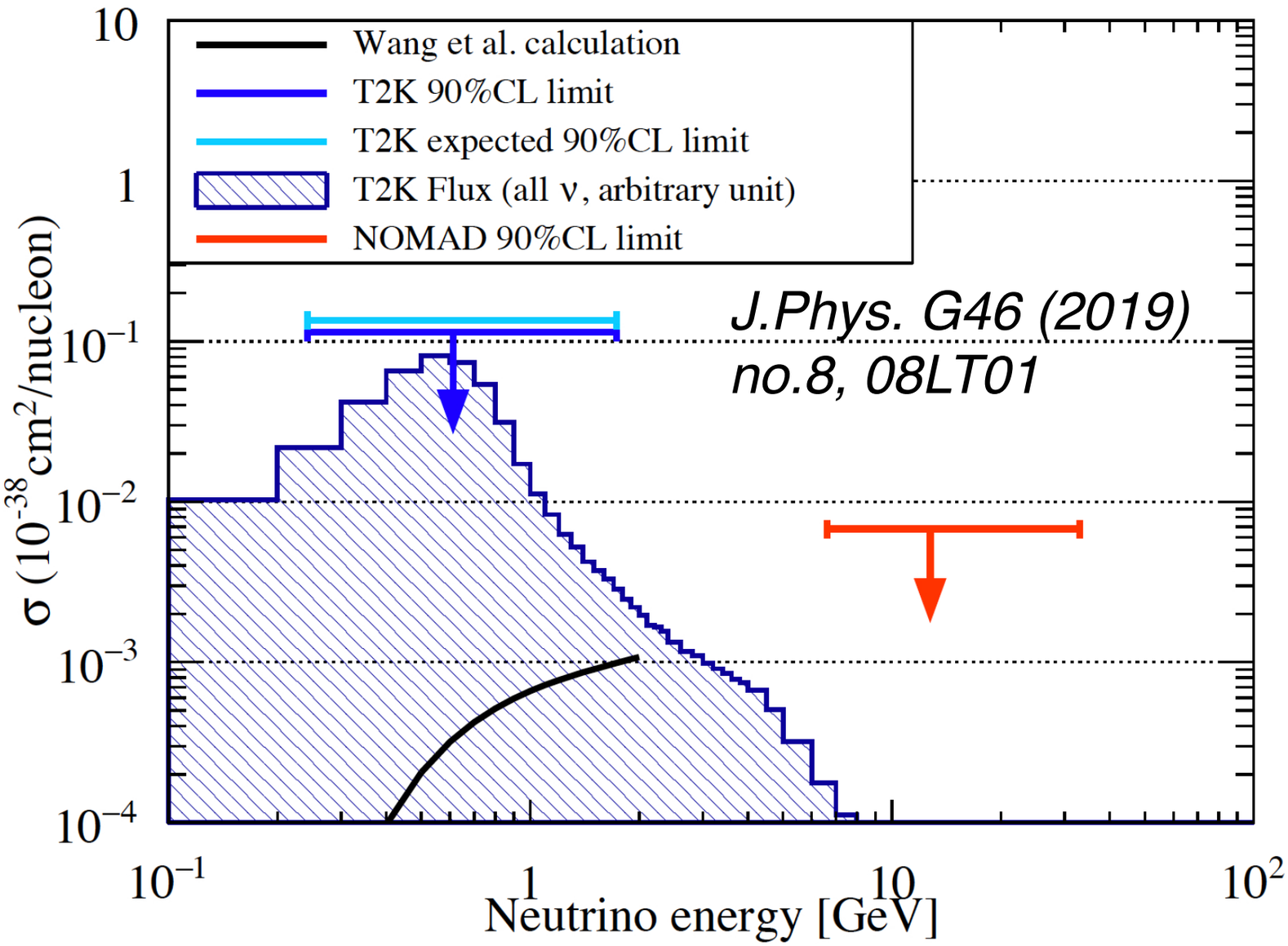
Neutral Current Measurements



J.Phys. G46 (2019) no.8, 08LT01

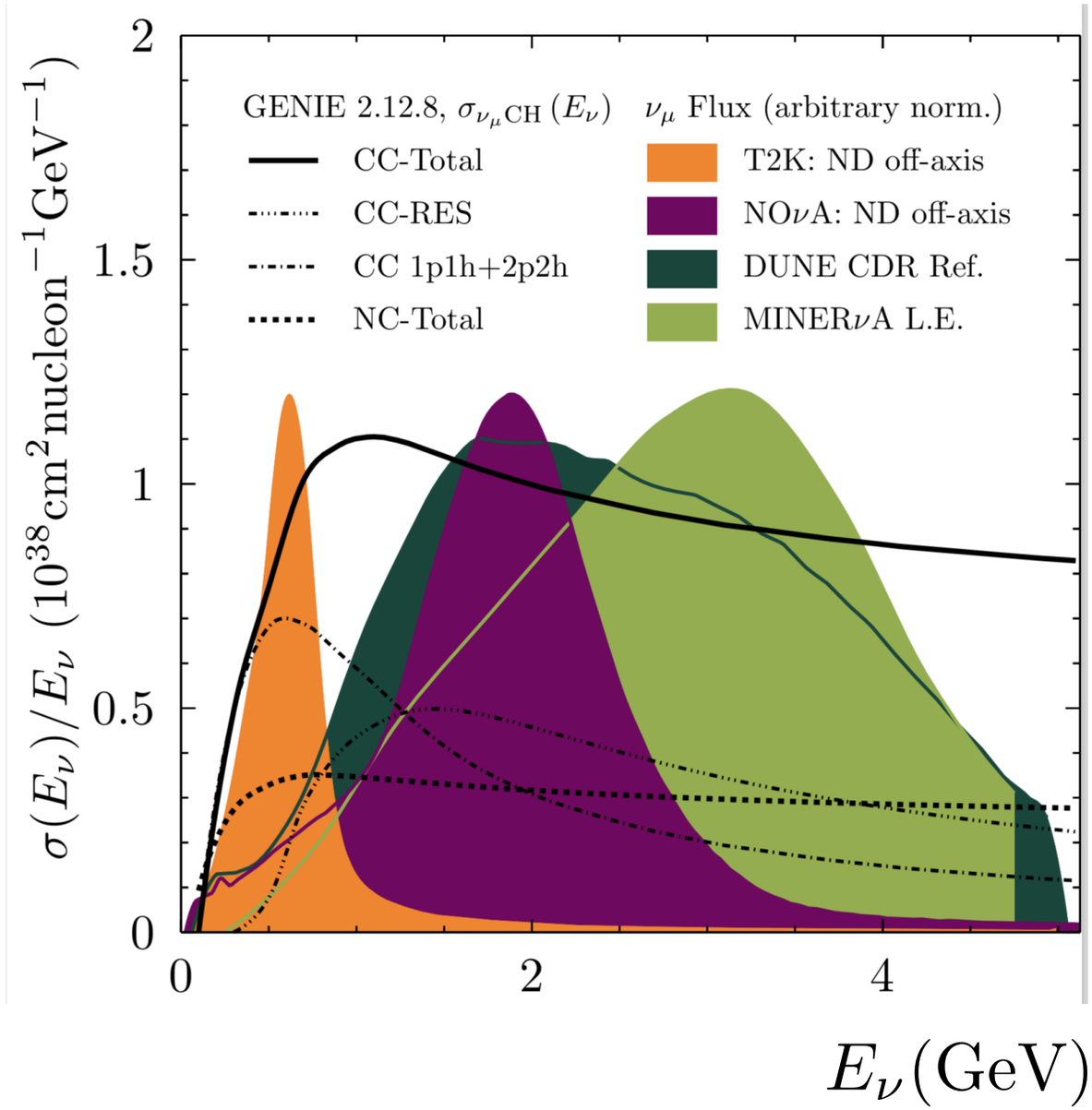
- NC1γ is a rare process which mimics ν_e appearance
- Difficult to isolate in the T2K near detector; challenges outlined for future experiments

Neutral Current Measurements



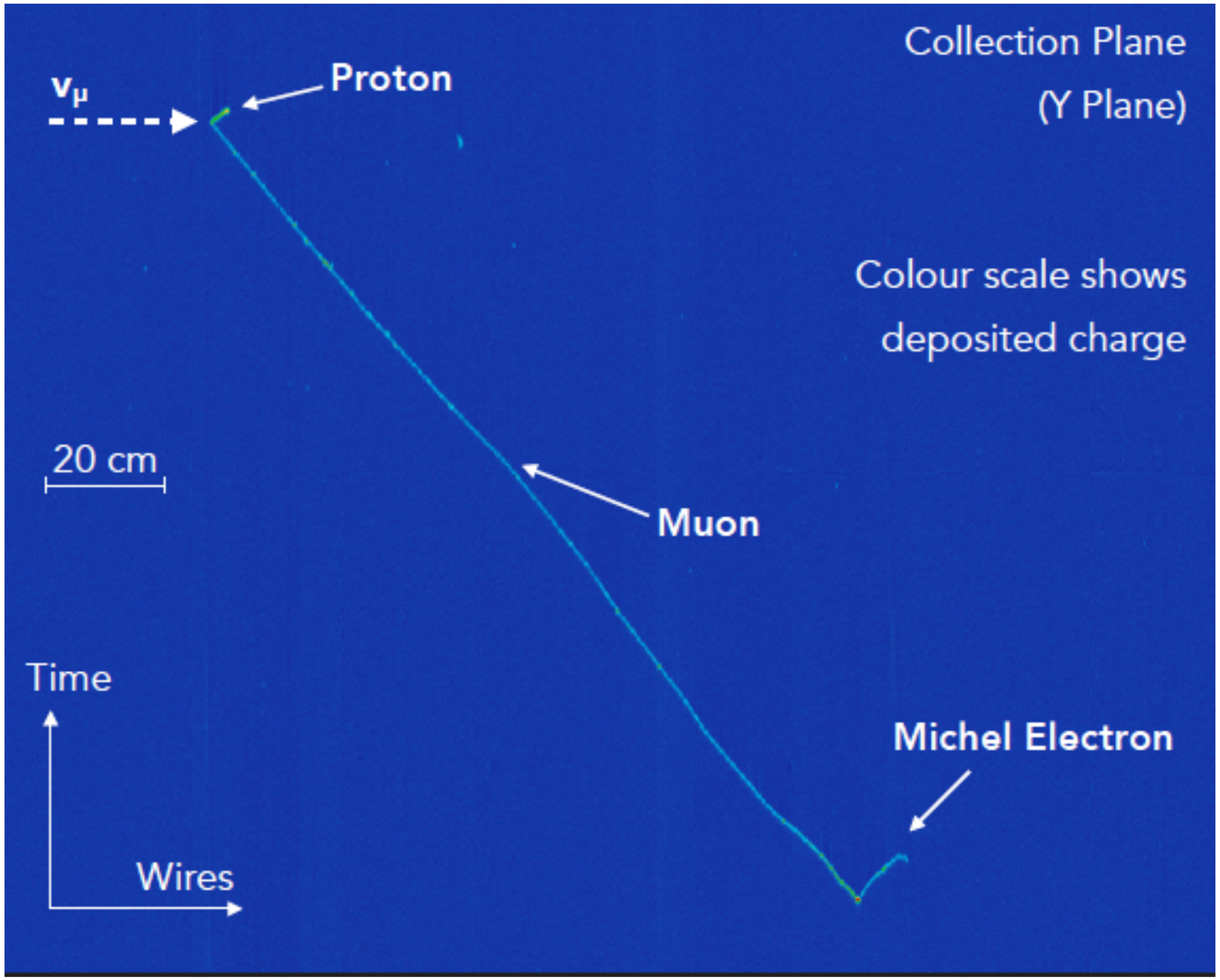
- NC1γ is a rare process which mimics ν_e appearance

- Difficult to isolate in the T2K near detector; challenges outlined for future experiments



+ CC inclusive

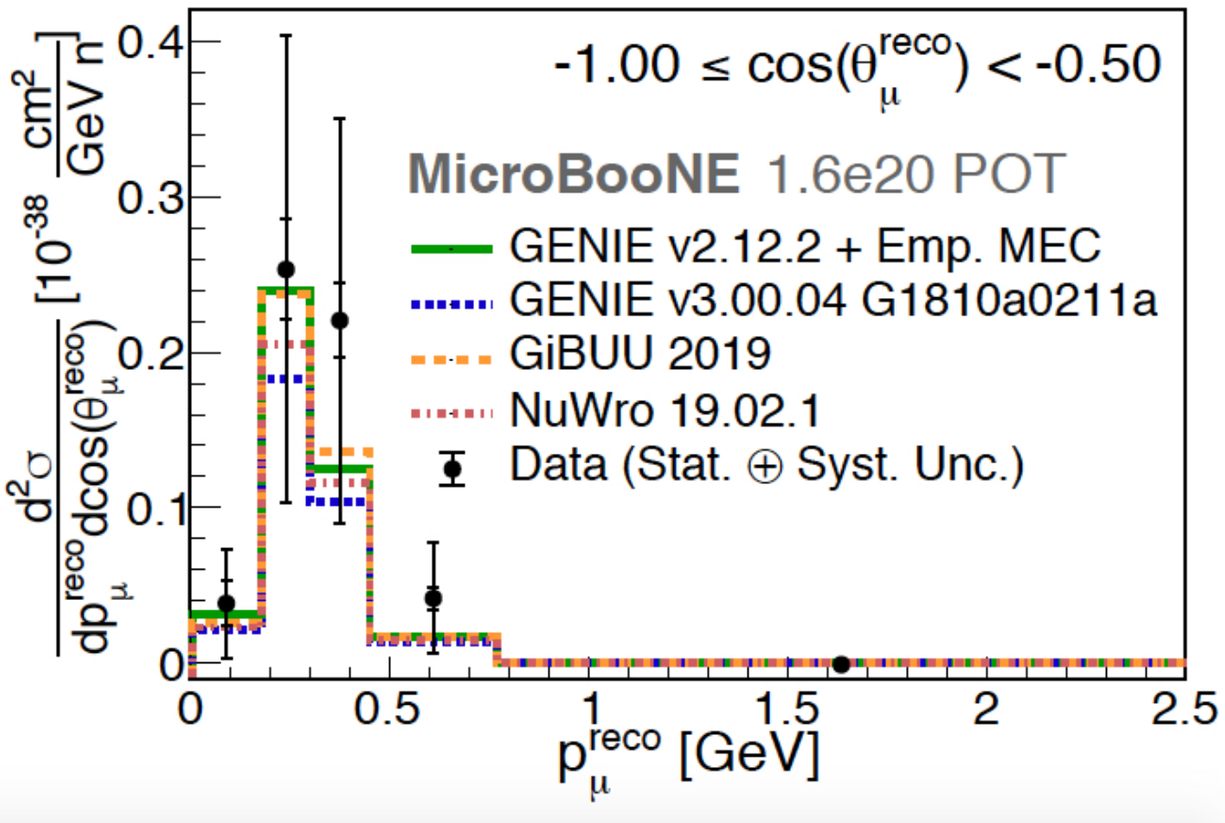
First MicroBooNE results!

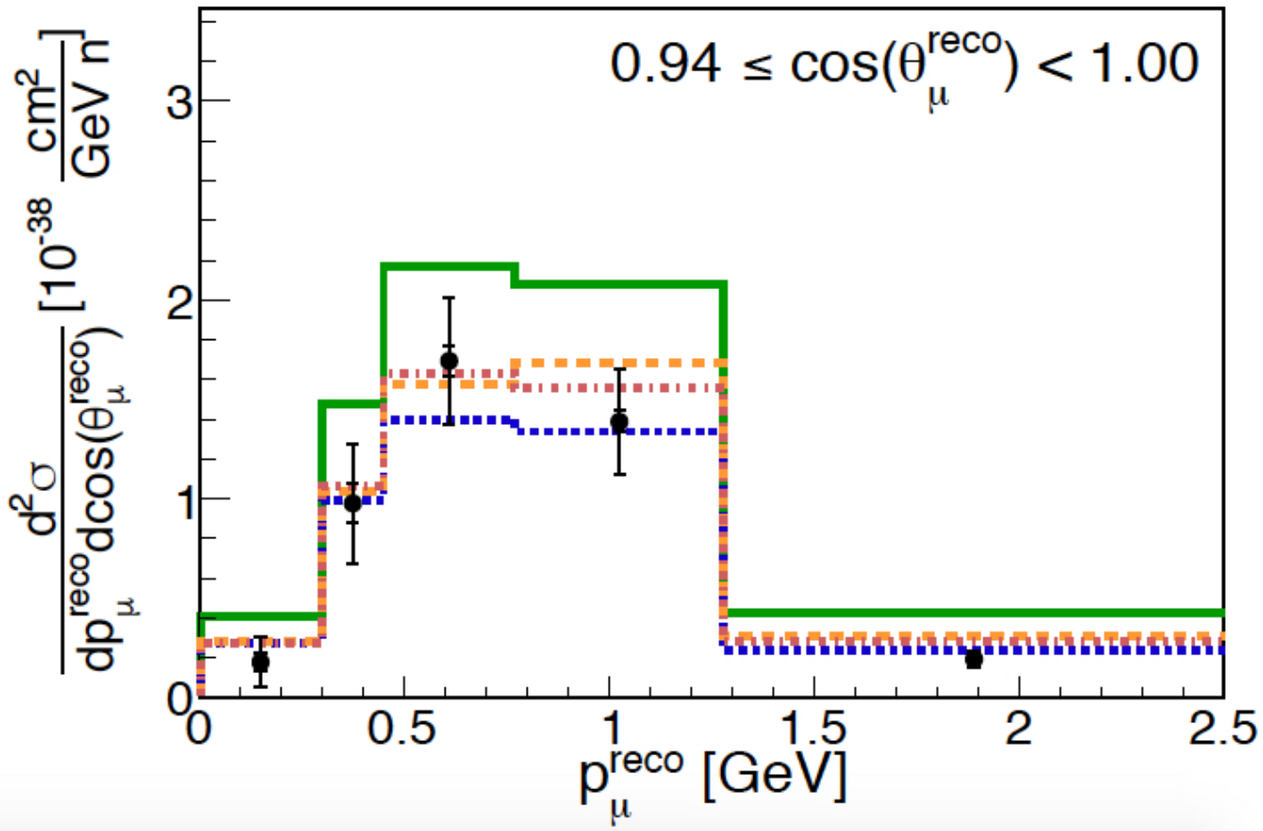


FNAL joint seminar

- CC inclusive: “Just” count muons
- Challenges: significant cosmic ray rejection, reconstruction

First MicroBooNE results!





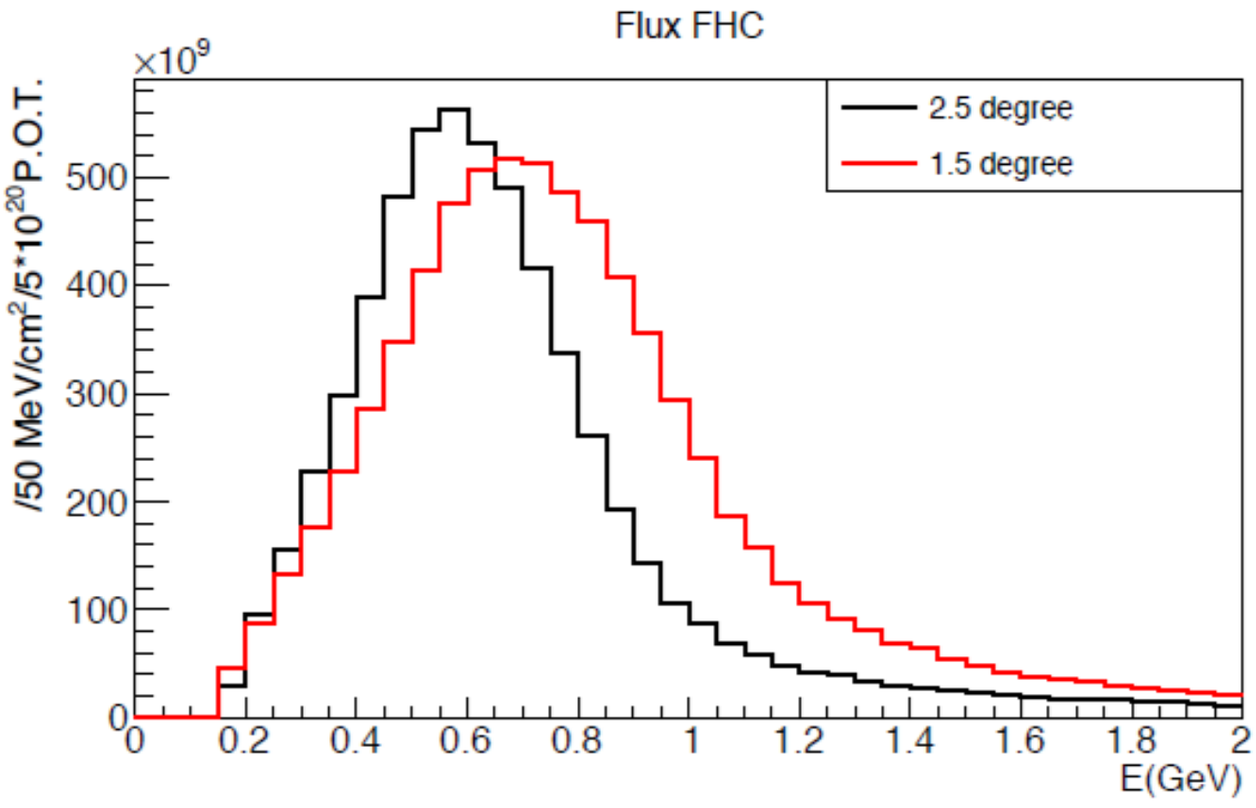
arxiv 1905.09694, submitted to PRL

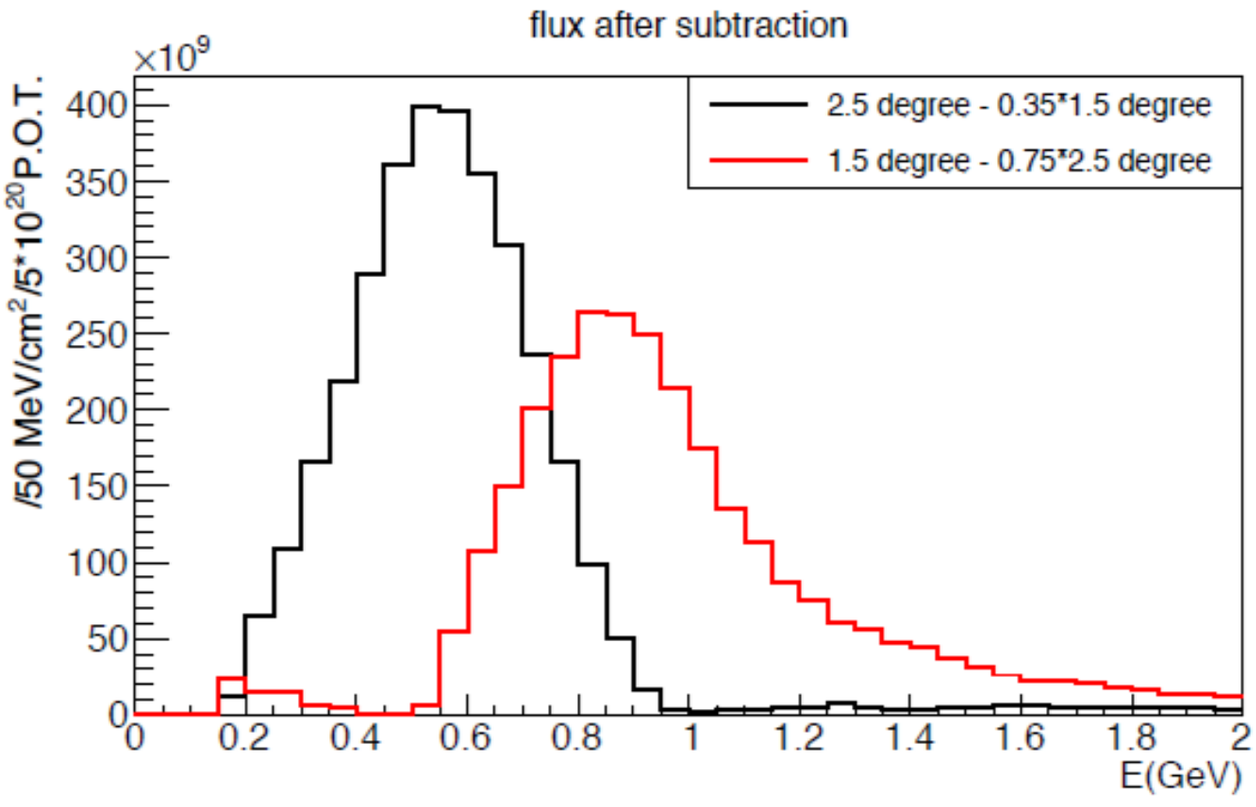
- Differential results; 'usual' forward region deficit better represented by newer models

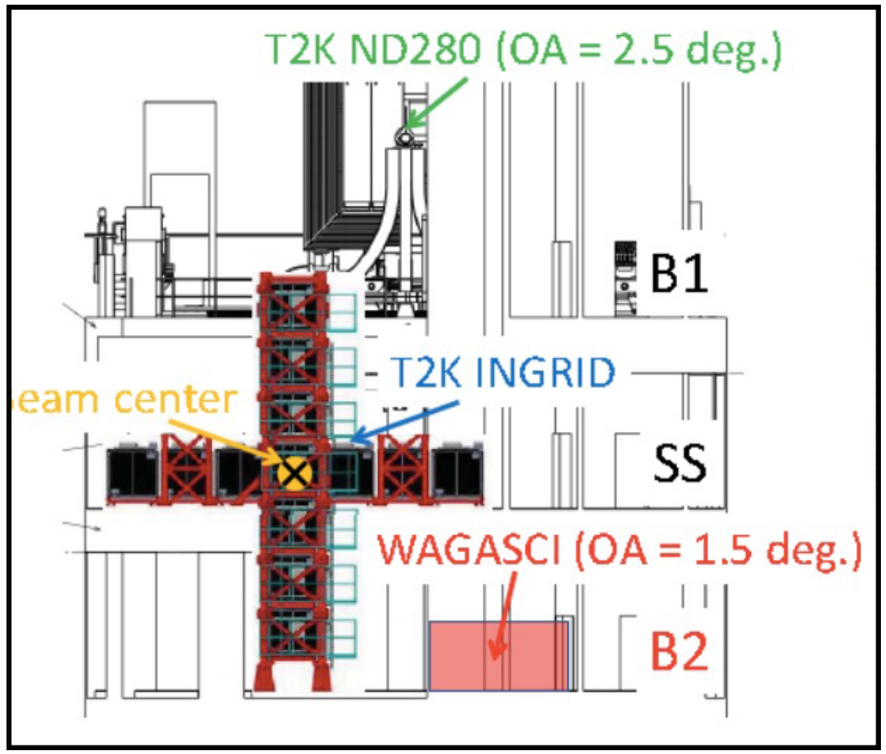
Outline

Future experiment ideas

New T2K detectors: WAGASCI+BabyMIND



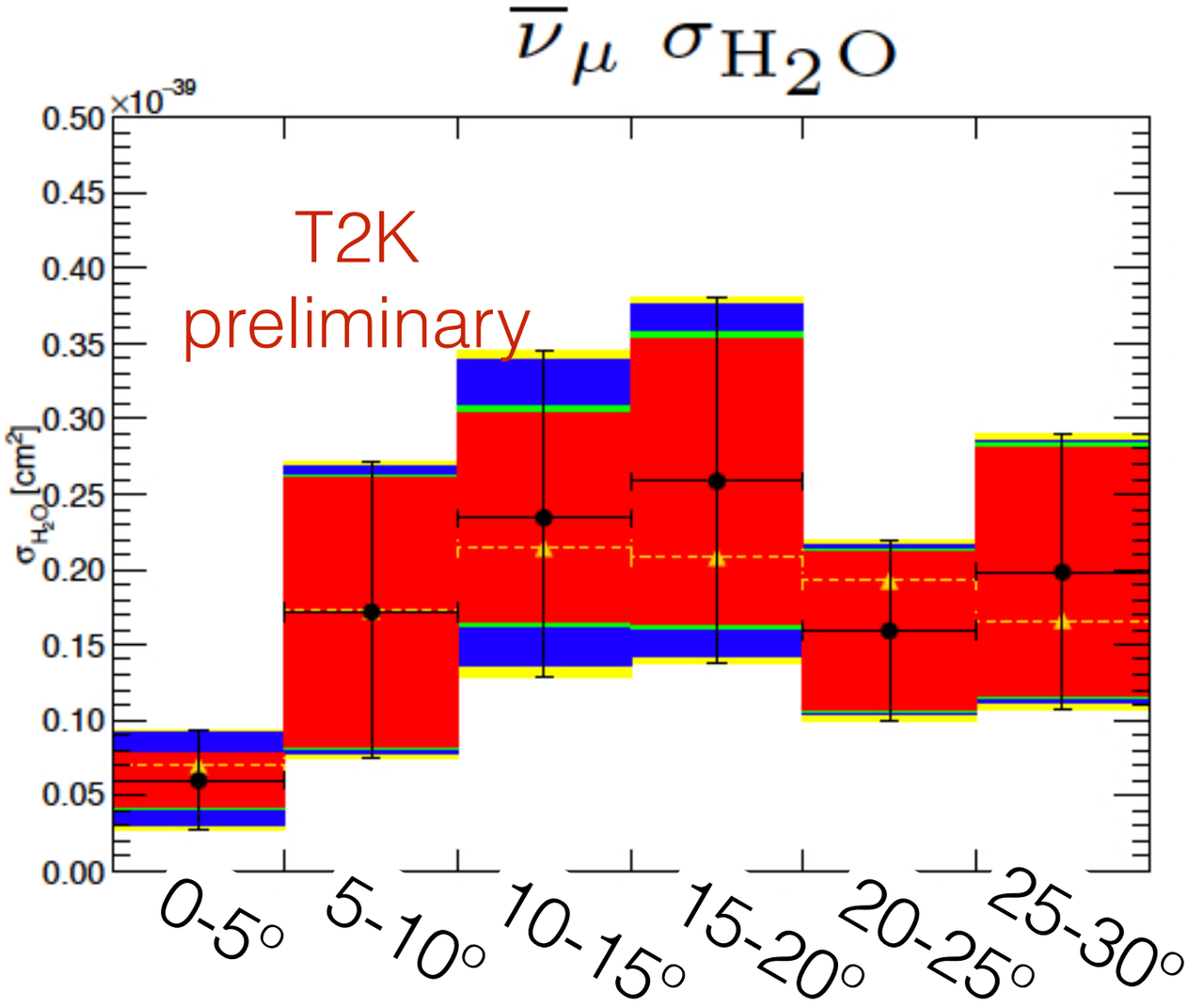




- WAGASCI+BabyMIND adds another off-axis point (1.5 deg) for water target

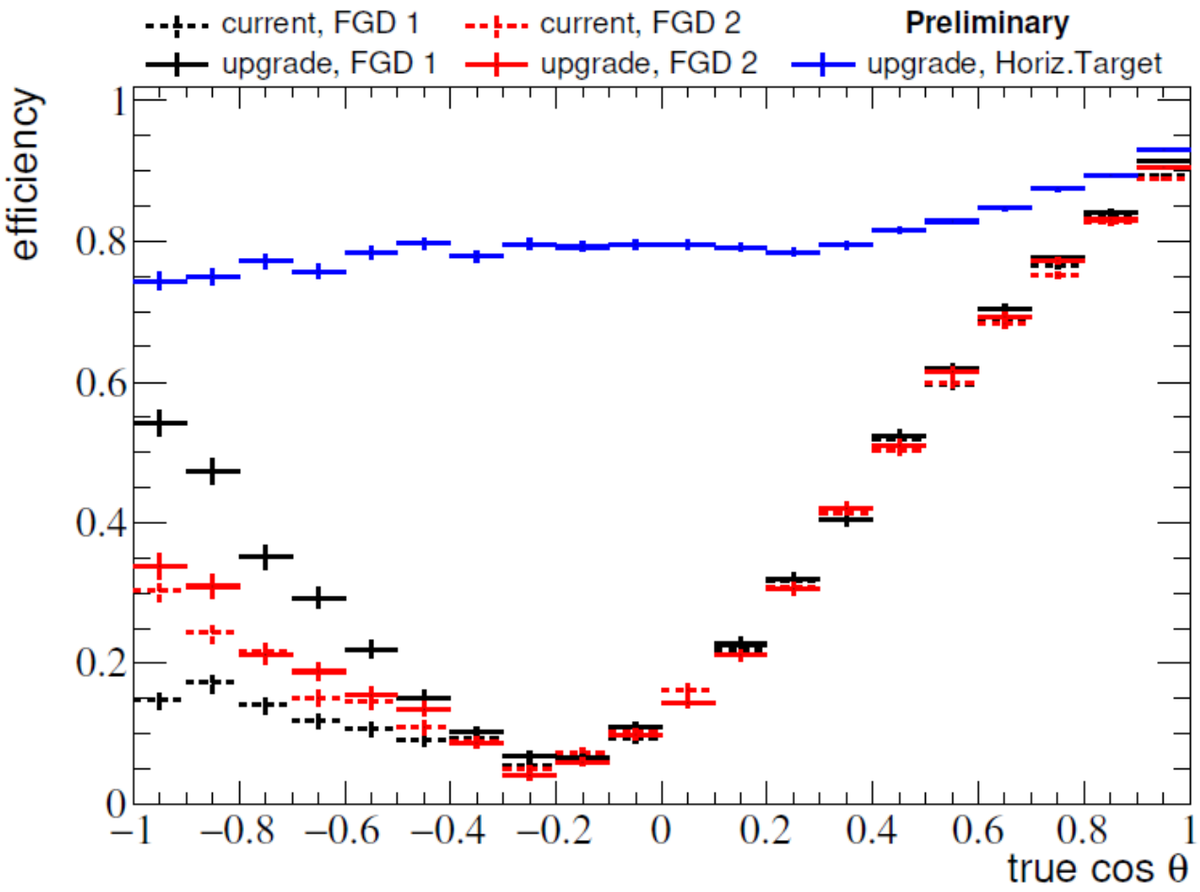
- Sign selection for neutrino, antineutrino separation

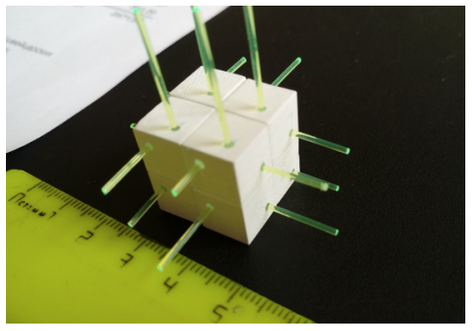
First WAGASCI results

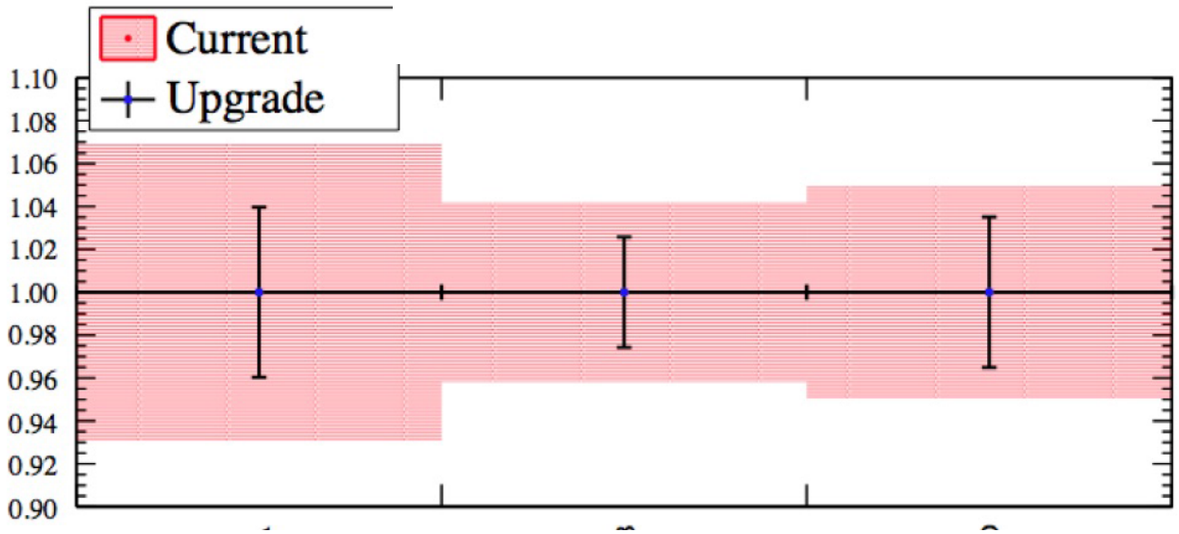


Limited acceptance CC antineutrino on water and CH, 1.5 deg axis flux

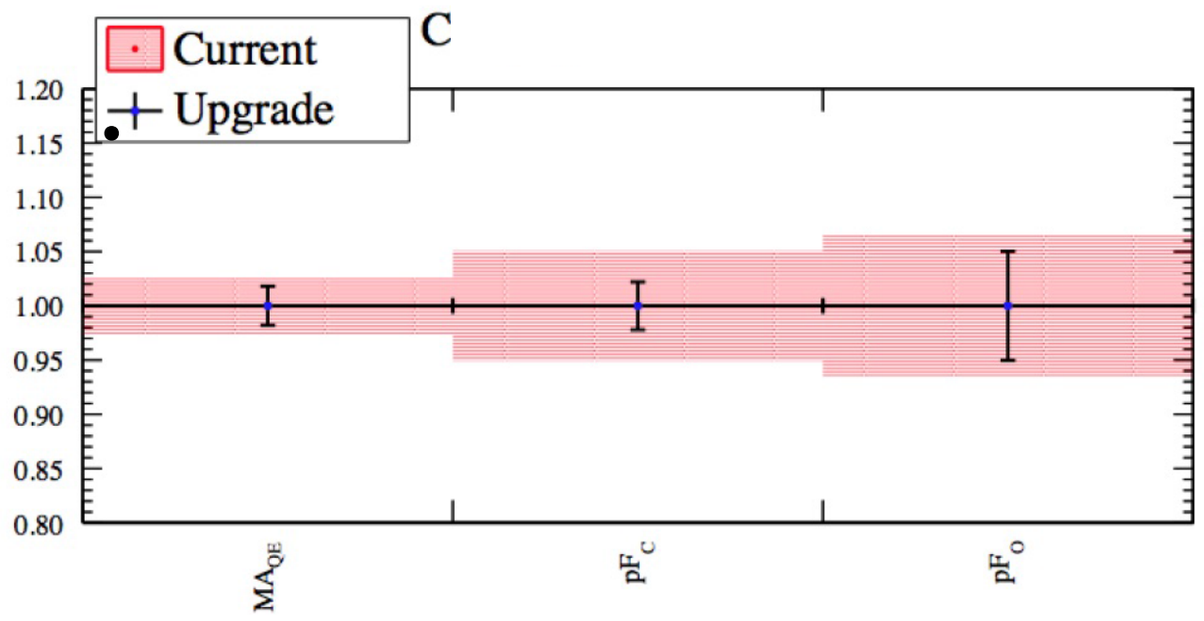
Future of T2K: ND upgrade







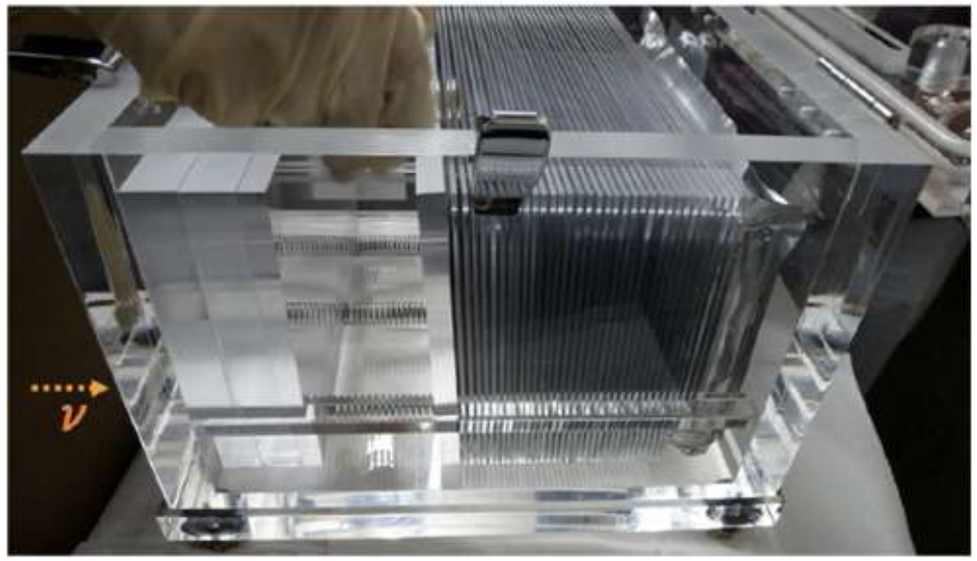
CCQE model parameters



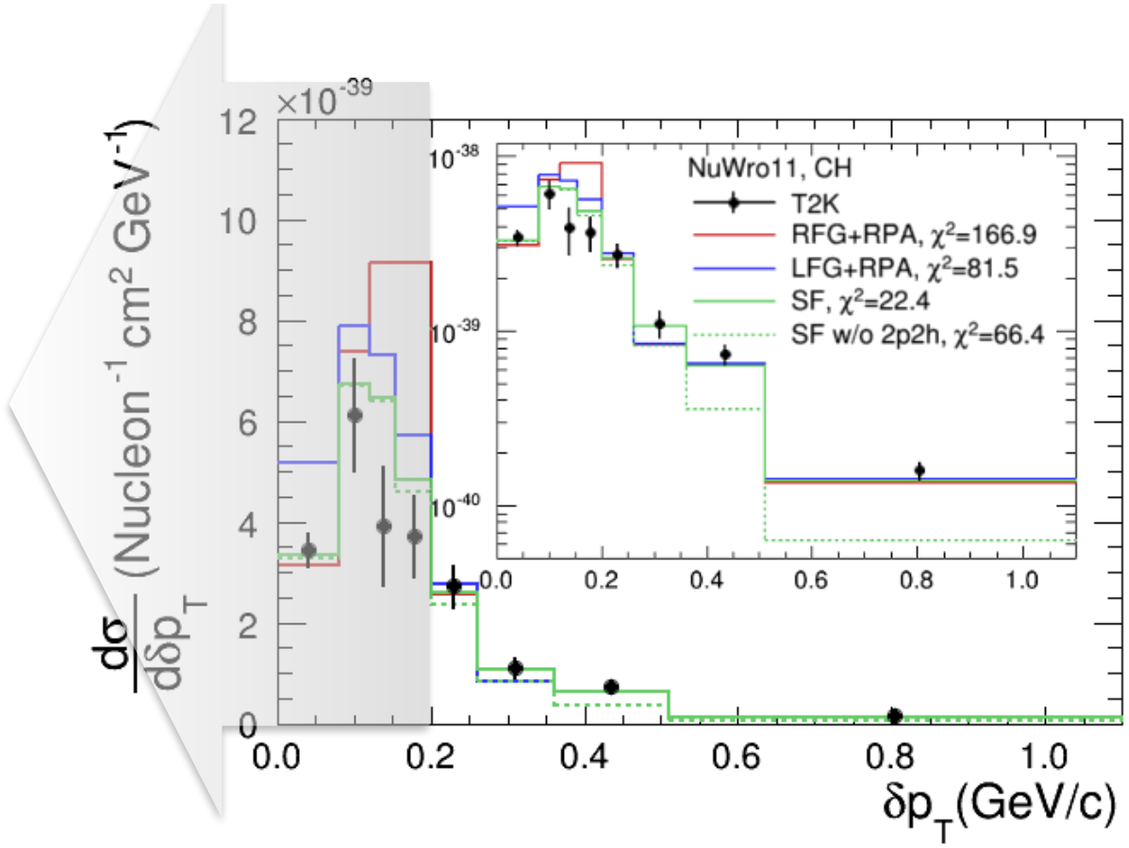
- ND upgrade will have improved acceptance compared to ND280
- Improved constraint of cross section models within oscillation analysis; improved statistics at high angle for cross section measurements

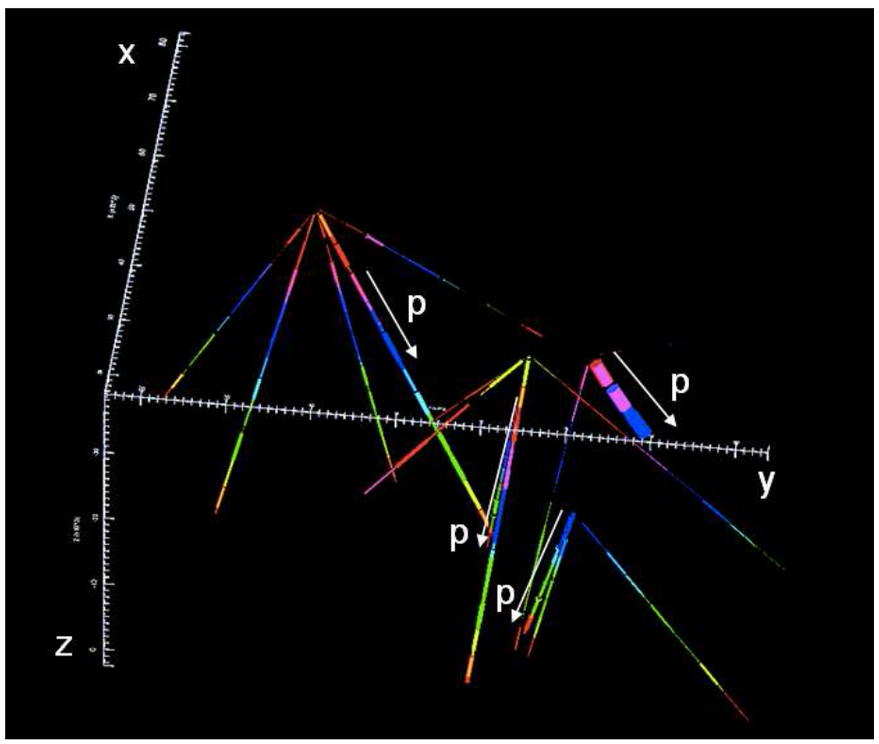
New experiment

NINJA



Water target + emulsion film





- Much lower threshold to protons: T_p~20 MeV vs. ND280 ~175 MeV
- Extend new window on models: multiplicity and kinematic variables of interest

Important technique: v-e scattering

$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}} \approx \frac{E_e}{1 - \frac{E_e\theta^2}{2m}}$$

- Single, forward electron; known cross section
- But, very limited rate

Important technique: v-e scattering

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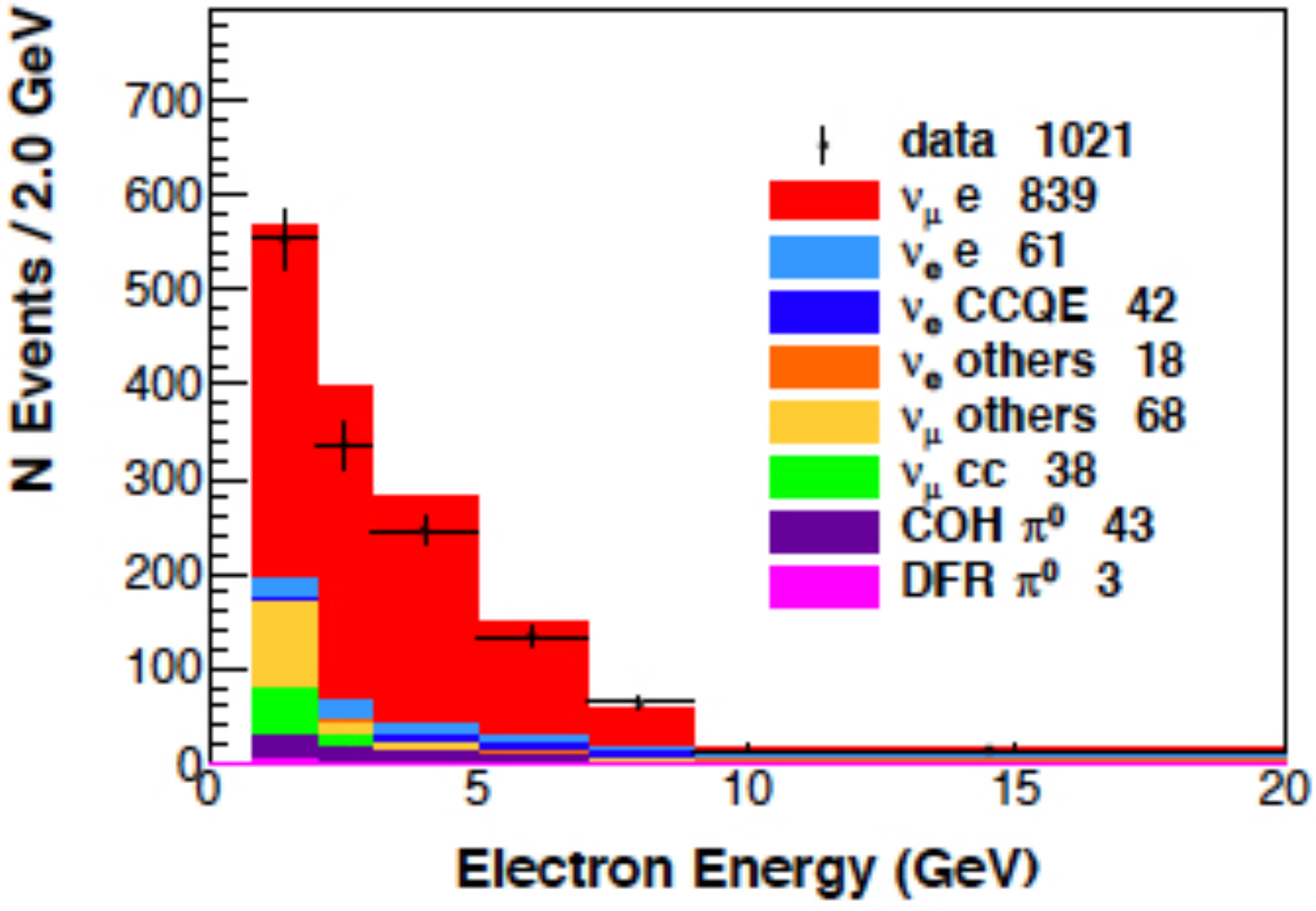

MINERvA: arxiv.1906.00111 and Phys. Rev. D 93, 112007

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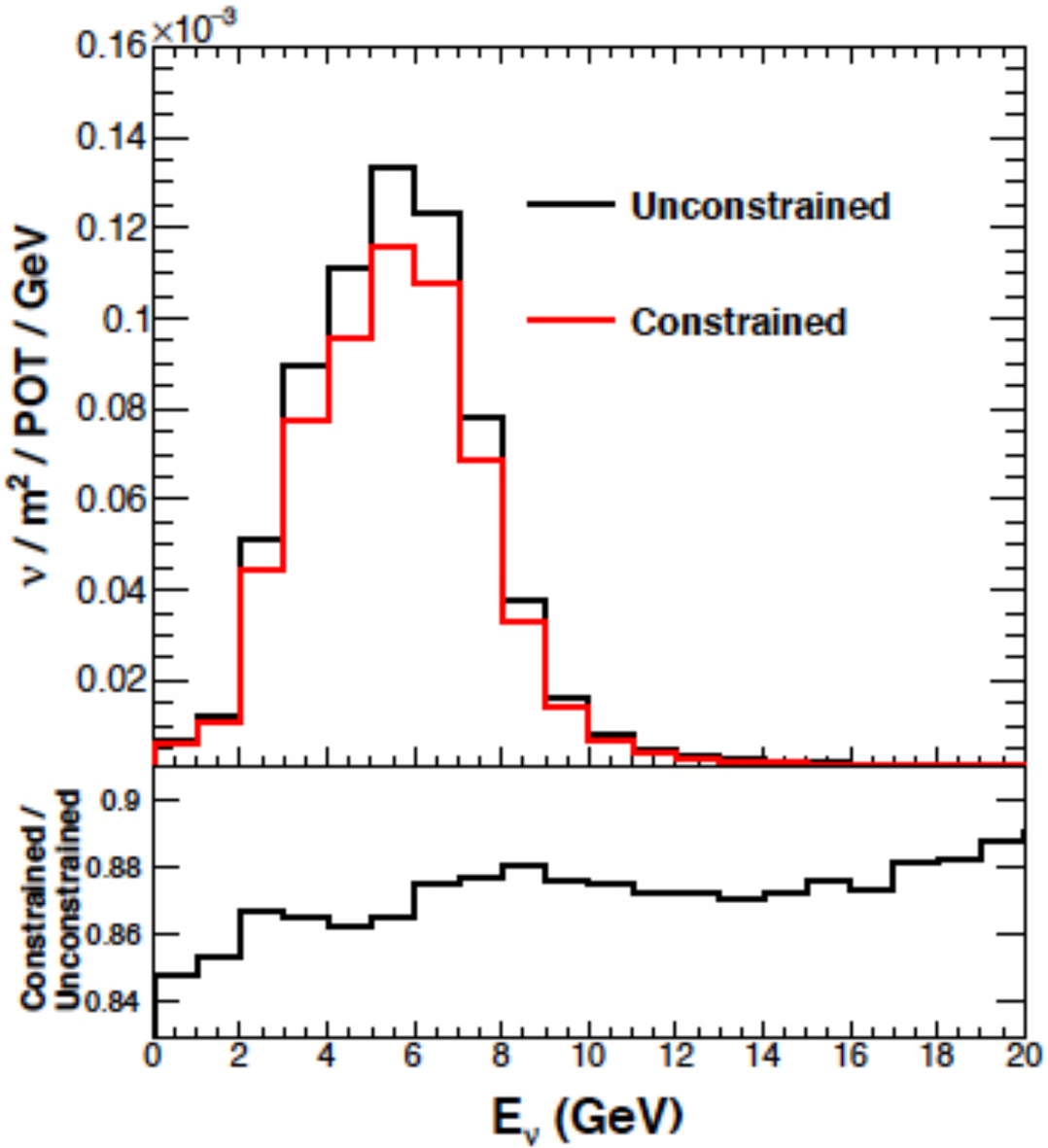
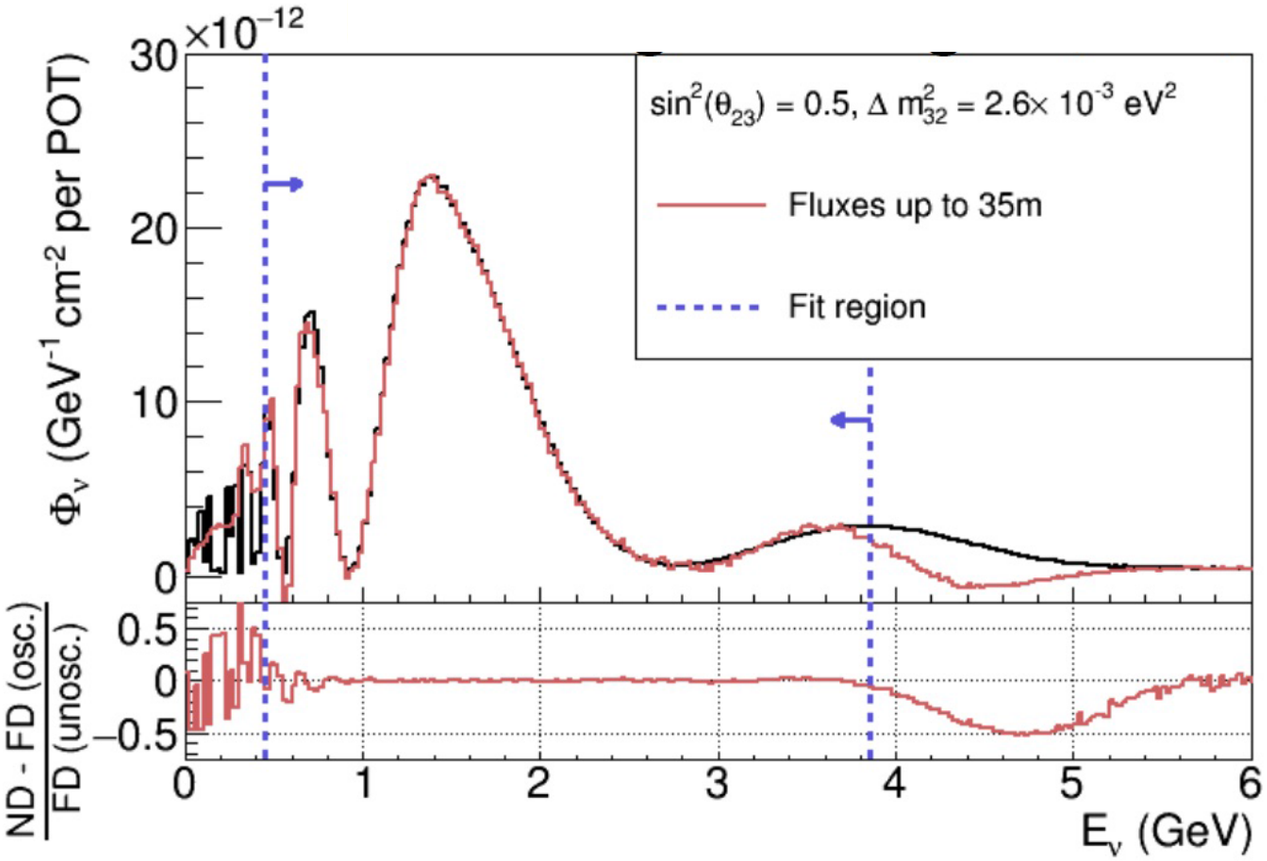
MINERvA: arxiv.1906.00111 and Phys. Rev. D 93, 112007

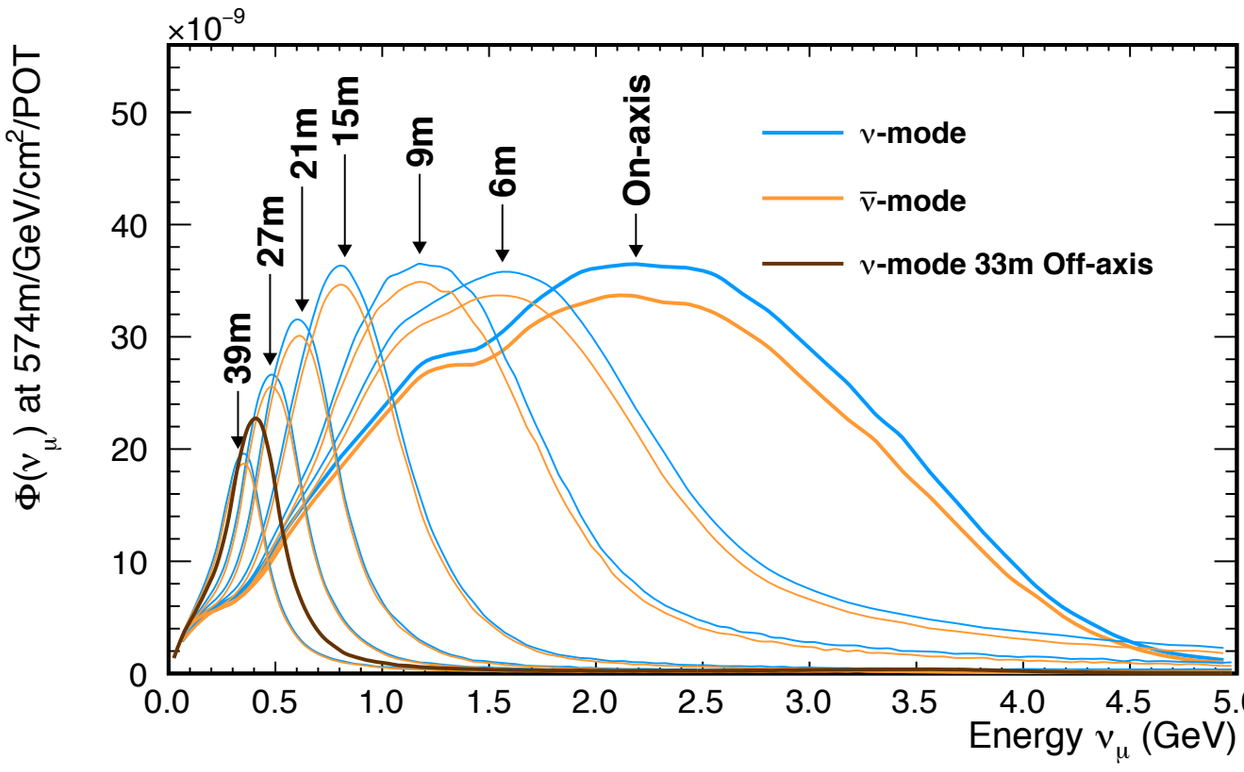
Significant tune to flux and reduction of uncertainties



Use of off-axis angles: νPRISM

Precision Reaction Independant Spectrum Measurement

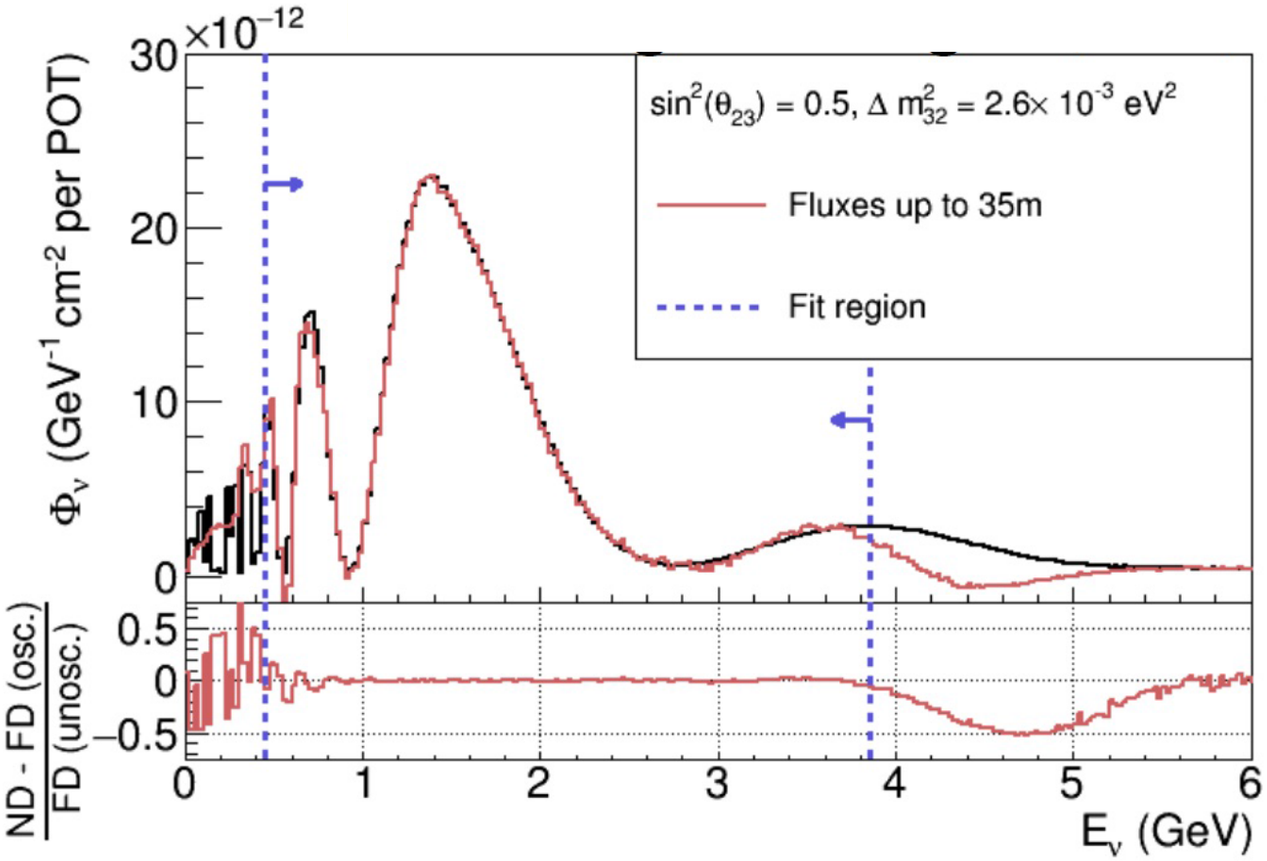


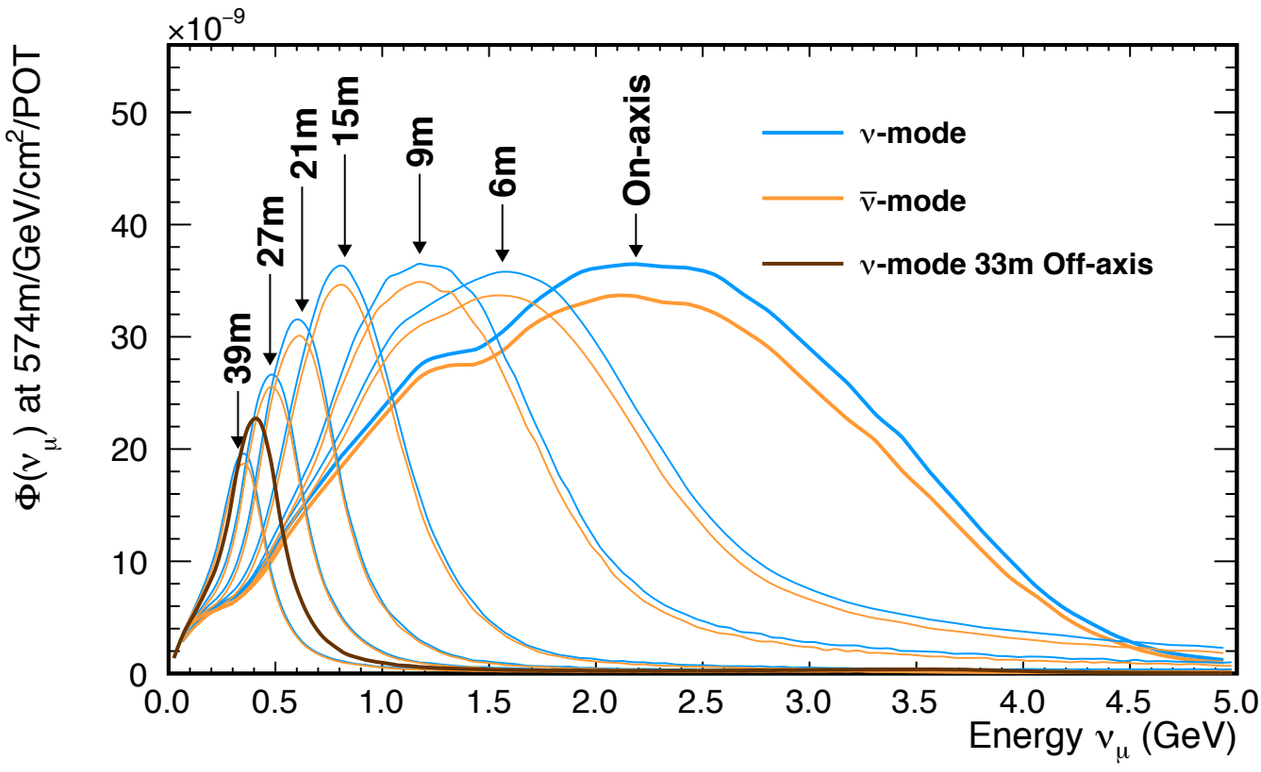


Linearly combine the spectra to create a pseudo-oscillated flux

Use of off-axis angles: νPRISM

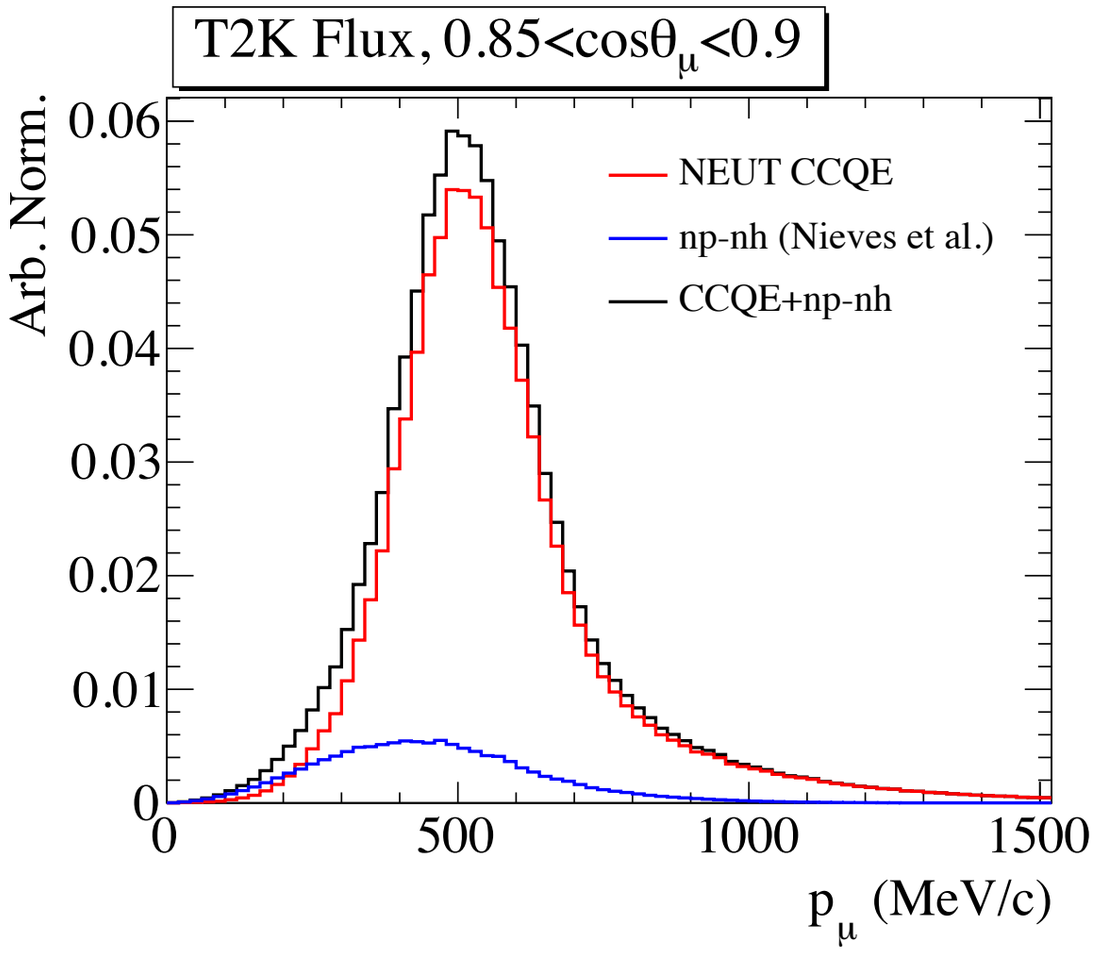
Precision Reaction Independant Spectrum Measurement

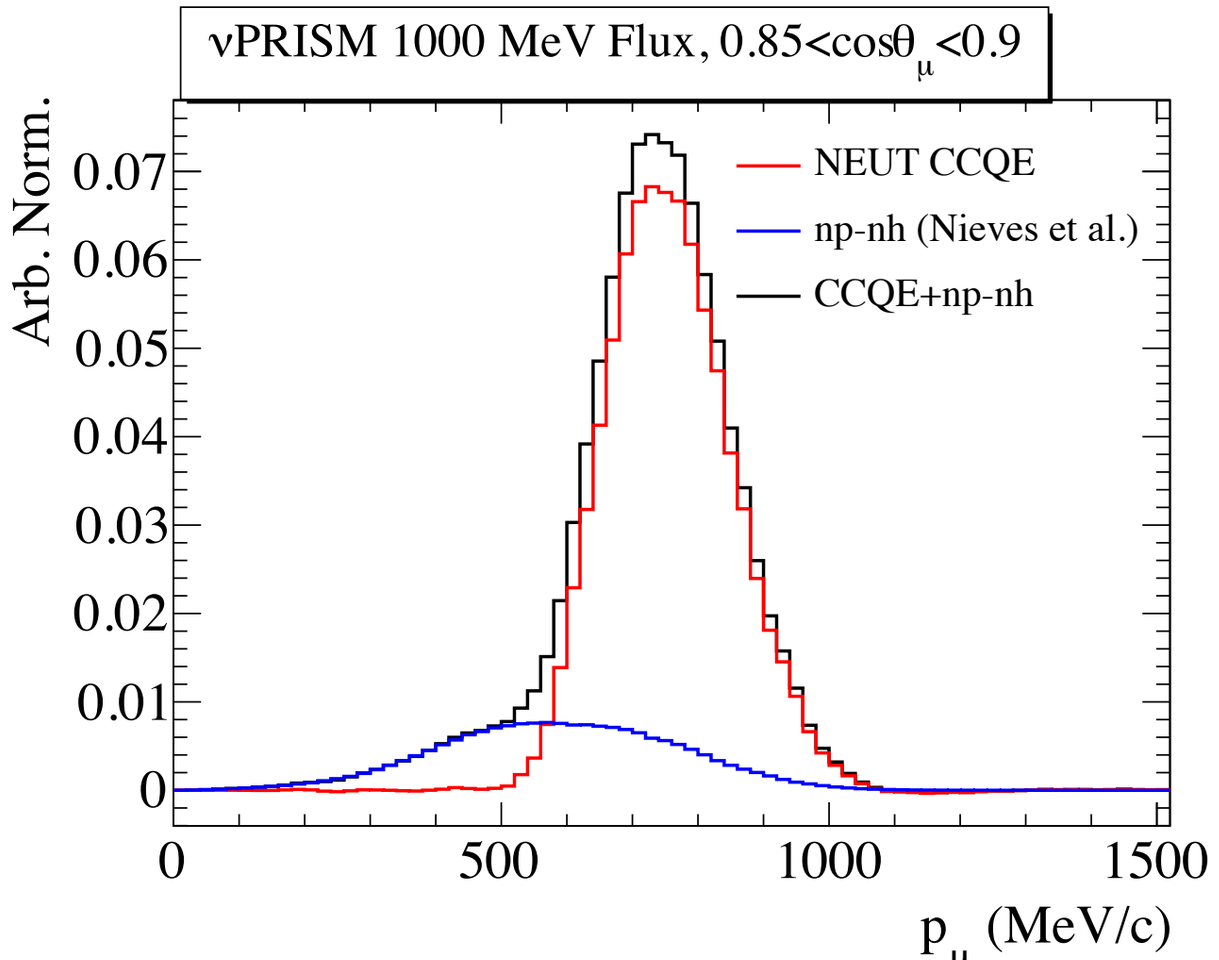




$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Matching is not perfect for on-axis case (DUNE) but changing beam line optics can improve HE tail agreement





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- Direct probe of response function
- Also: <3% statistical uncertainty on electron neutrino cross section
  - Significant uncertainty for T2K (dominant for Hyper-Kamiokande)

Summary

- Robust modelling of neutrino-nucleus interaction models are critical to a variety of physics experiments

- Many different communities contribute to improved modelling electron scattering data, **neutrino scattering data**, theory groups, and simulation developers

Summary

- New approaches from a variety experiments (MINERvA, T2K) have led to an improved understanding of **QE and 2p2h**

Movement to a semi-inclusive description;
2p2h final state kinematics. Neutrons!

Summary

- New approaches from a variety experiments (MINERvA, T2K) have led to an improved understanding of QE and 2p2h
- **Single pion production** puzzles are pernicious! Please persist.

Low Q2 deficits?

What physics is missing to explain the pion spectra?

Is there 2p2h-like processes?

- New data from MicroBooNE and NOvA is important going forward

Summary

- Experiments with novel detection (NINJA, ANNIE) will join the global effort
- Future near detectors may make powerful use of techniques including: **v-e scattering, off-axis angles**, to reduce uncertainties associated to the interaction model

Thank you for the invitation and your attention!

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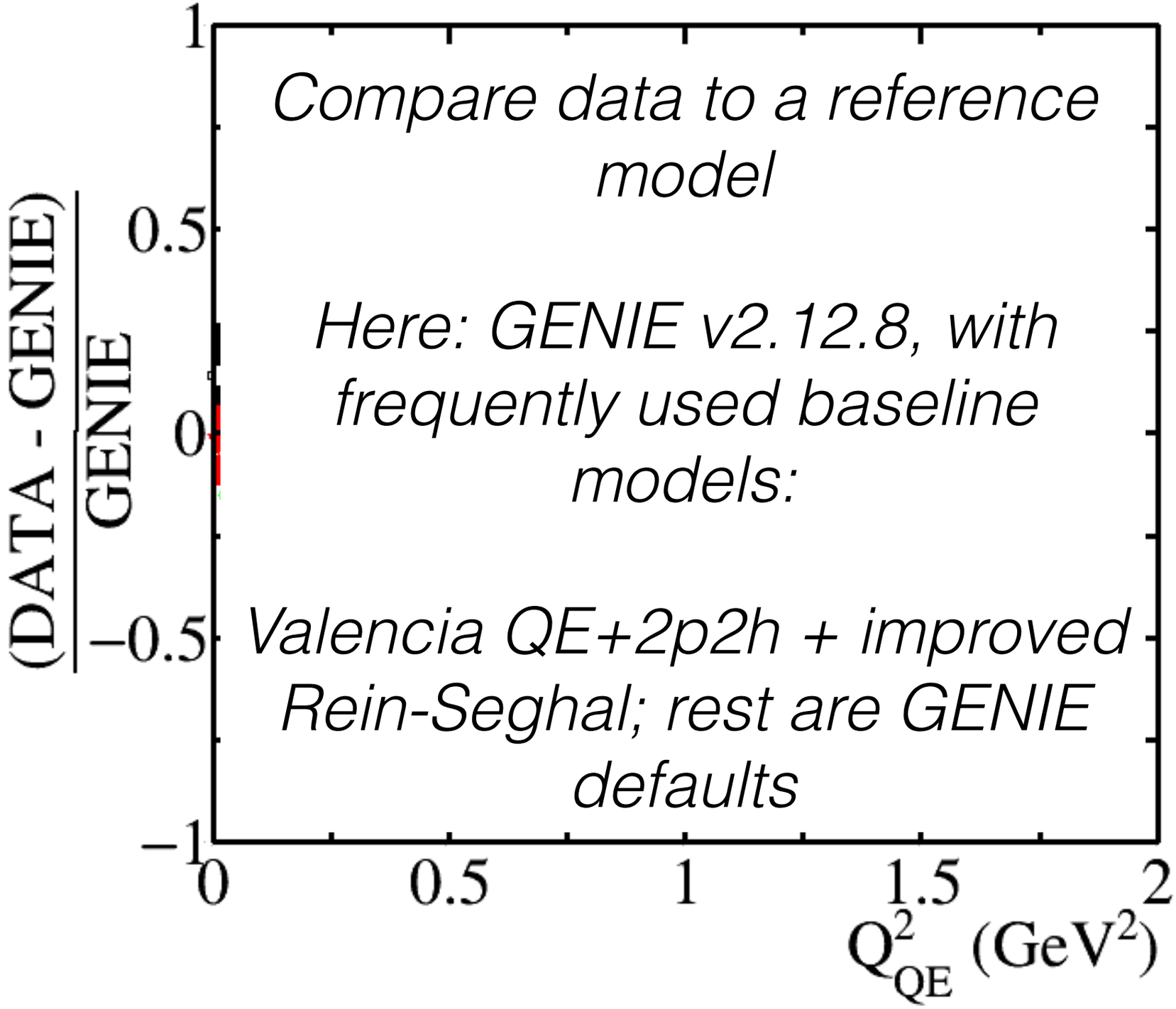
Another view of data / model comparisons



From Annual Reviews article (Mahn, Marshall, Wilkinson arxiv.1803.08848)