Measurement of Antineutrino and Neutrino CC Inclusive cross section and their ratio in MINERvA

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(Presented by Jeff Nelson of W&M)

L. Ren et al., PRD 95 (2017) no.7, 072009
L. Ren, PhD Thesis, University of Pittsburgh, 2017

Outline

- Motivation
- Game plan: Low nu flux method
- Sample selection and flux extraction
- Systematic Uncertainties
- Results

Motivation

- ✤ Long baseline oscillation experiments aim to precisely measure neutrino oscillation parameters and constrain CP violation using antineutrino and neutrino beams
- ✤ CP asymmetry can be measured in terms of the probability ratio:

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})}$$

- ✤ This is primarily sensitive to antineutrino to neutrino cross section ratio ($R_{CC} = \frac{\sigma_{\bar{\nu}}}{\sigma_\nu}$)
- ✤ Experiments like PINGU, where antineutrino/neutrino fluxes are large, are more sensitive to the cross section ratio
- ✤ Reducing systematic uncertainties in antineutrino and neutrino cross section, especially in their ratio, is essential to achieving desired sensitivity
- ✤ Precise ratio can be used to tune models to improve knowledge of interaction cross sections
- ✤ Common detector and model related systematic uncertainties cancel in the cross sections ratio measured using the same detector and flux method

Game Plan: Low nu Flux Method

- One of the largest uncertainties in accelerator based experiments comes from flux prediction
- Nearly standard-candle process for flux measurement; previously used by CCFR, NuTeV, MINOS
- Relies on CC event rates at low recoil energy $\nu = E_{had} = E - E_{\mu}$
- The cross section for CC Inclusive neutrino-nucleus scattering is:

$$\frac{d\sigma^{\nu,\bar{\nu}}}{d\nu} = A\left(1 + \frac{B^{\nu,\bar{\nu}}}{A}\frac{\nu}{E} - \frac{C^{\nu,\bar{\nu}}}{A}\frac{\nu^2}{2E^2}\right)$$

A, B and C depend on structure functions

- In the limit of low energy transfer ($\nu/E -> 0$) , antineutrino and neutrino cross sections are independent of neutrino energy
- Due to energy independence, the interaction rate is proportional to the flux
- Use extracted event rates to measure neutrino and antineutrino fluxes
- Then extract inclusive scattering cross section using those fluxes

Not So Simple

- Can't cut exactly at $\nu = 0$; Need to put in corrections from other structure functions

$$S^{\nu}(\bar{\nu})(\nu_0, E) = \frac{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E)}{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E \to \infty)}$$

→ Integrated cross section at energy (E)

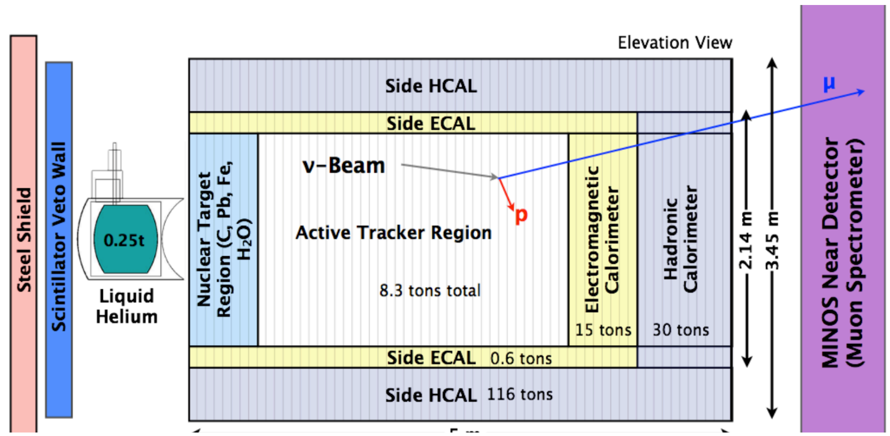
→ Integrated cross section in the high energy limit

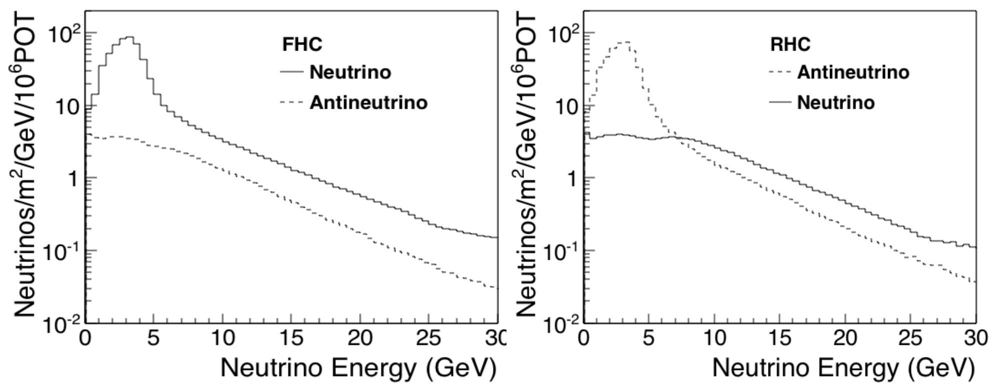
- Use modified GENIE 2.8.10 (AKA Hybrid GENIE) to get these corrections
  - Improved modeling of low-nu cross section components
  - For QE events, include Random Phase Approximation (RPA) model, to account for long range nucleon-nucleon correlation
  - Also include valencia 2p2h model contribution
  - Reduce GENIE single pion non-resonant component by 57 % which improves agreements between ANL and BNL Data [1]

[1] P. Rodrigues et al. Eur. Phys. J. C 76, 474 (2016)

MINERvA

- Finely segmented solid scintillator detector on axis in NuMI beamline
  - Active tracker is all scintillator
  - Calorimeters are scintillator with Fe or Pb
- MINOS near detector for muon spectrometer
- Data collected in both forward (FHC) and reverse horn current (RHC) mode of NuMI
- Data collected in both low energy (LE) and medium energy (ME) NuMI tune
- Today's results uses data from LE tune

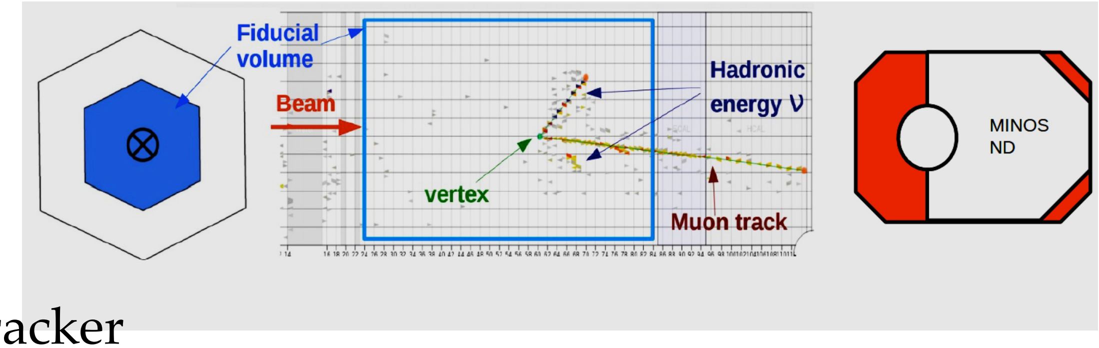




Predicted Neutrino fluxes in MINERvA
for FHC and RHC mode in Low Energy NuMI tune

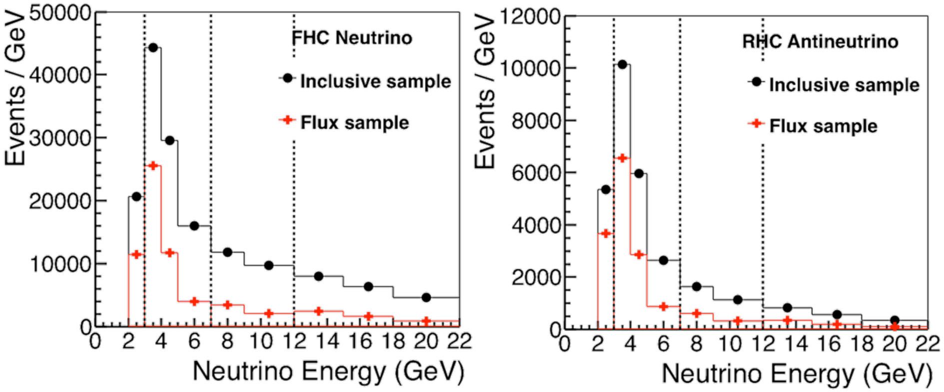
L. Aliaga et al, PRD 94, 092005 (2016)

Sample Selection



- CC Inclusive Sample
  - Events with a long track originating from fiducial volume of the MINERvA tracker and extrapolating into MINOS ND (muon track)
  - Clusters not associated with the muon track form recoil system
- Flux Sample
  - Choose CC Inclusive events below maximum (ν_0), which varies with neutrino energy to keep energy dependent contributions small

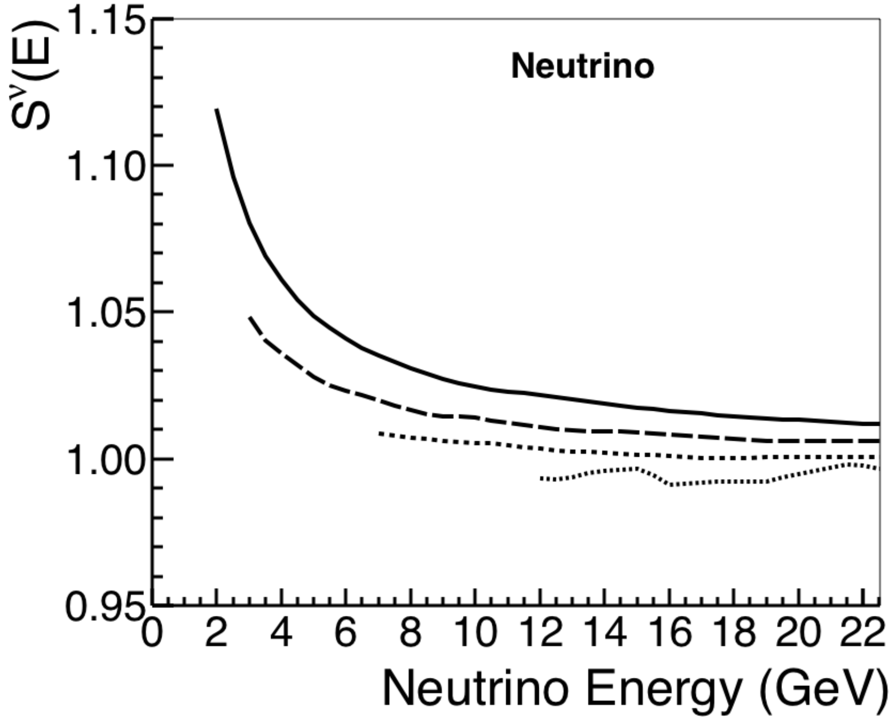
Acceptance corrected yields

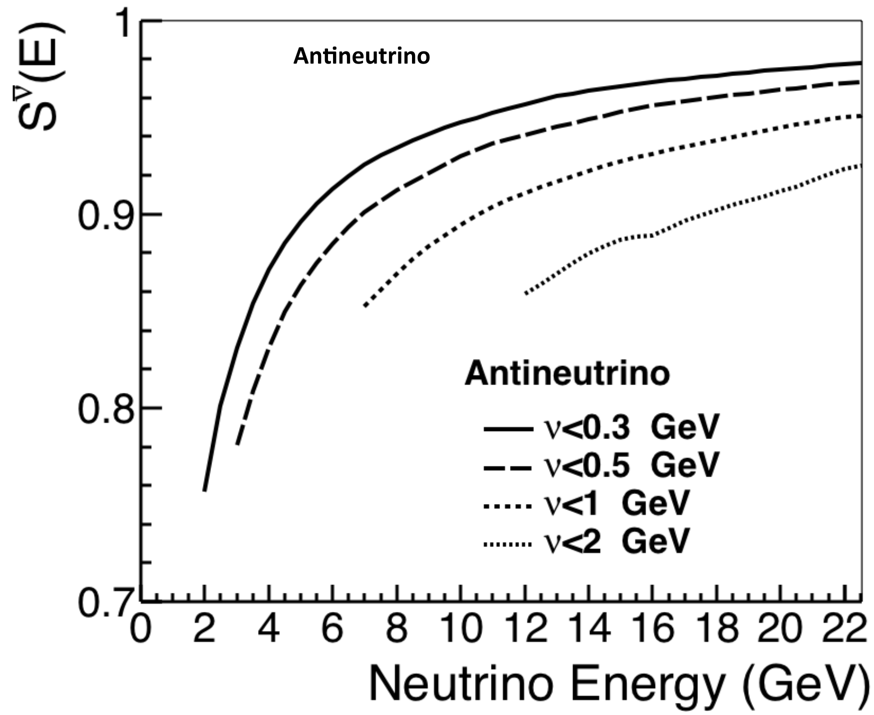


ν_0 (GeV)	Neutrino Energy Range (GeV)
0.3	< 3
0.5	3 < E < 7
1.0	7 < E 12
2.0	E > 12

Low nu Flux Correction

$$S^{\nu}(\bar{\nu})(\nu_0, E) = \frac{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E)}{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E \to \infty)}$$





Correct flux yield with this low-nu correction

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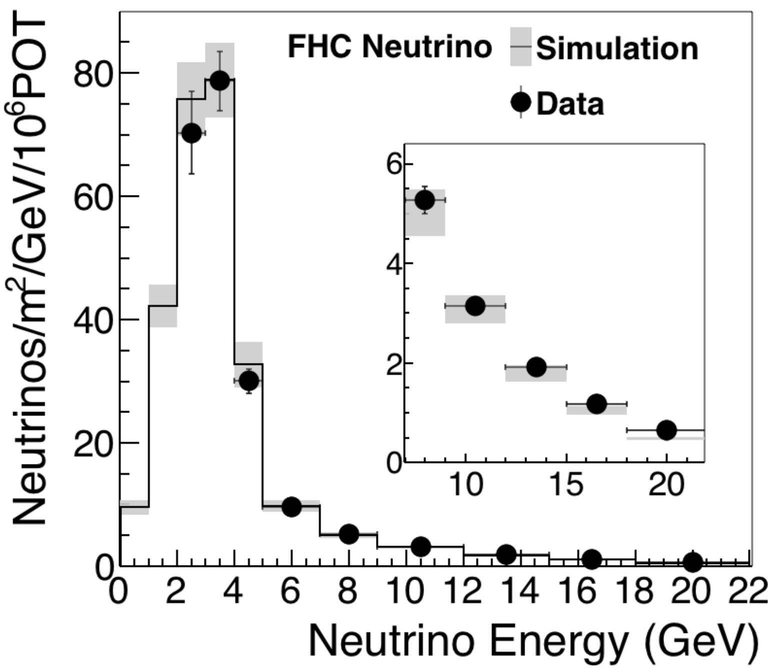
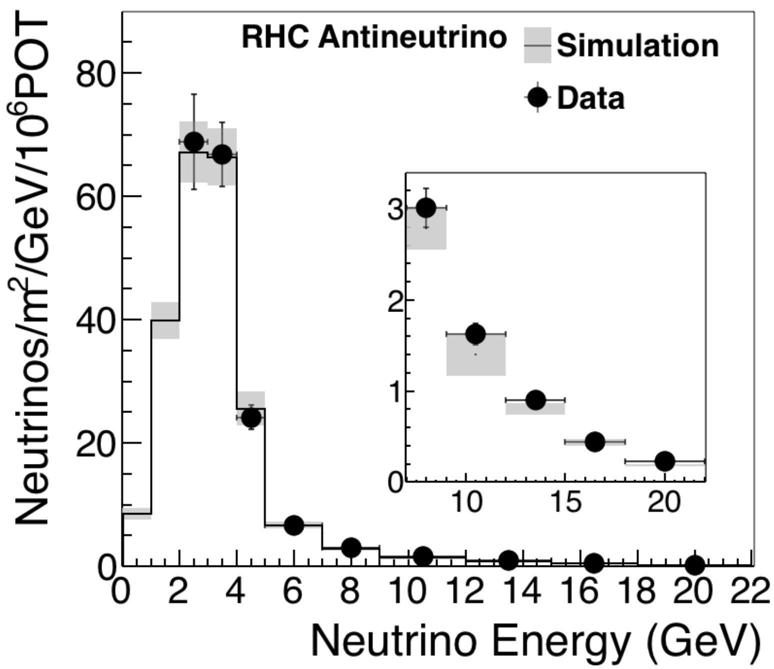
Low nu Flux

Additionally normalize flux using external cross section data on Carbon from NOMAD[1], which overlaps in our normalization bin with neutrino energy 12-22 GeV





[1] Q. Wu et al. (NOMAD Collaboration), PLB 660, 19 (2008)

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Systematic Uncertainties on Flux

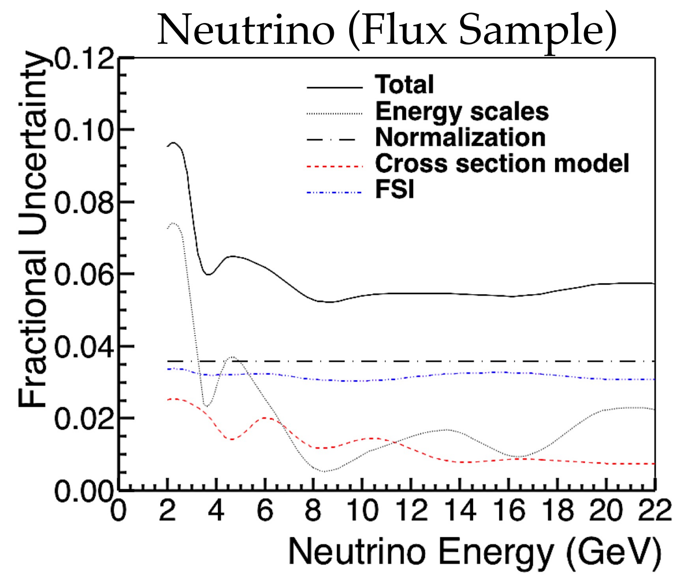
✤ *A priori* Flux
- Hadron production/beam focusing → largely unimportant in this analysis

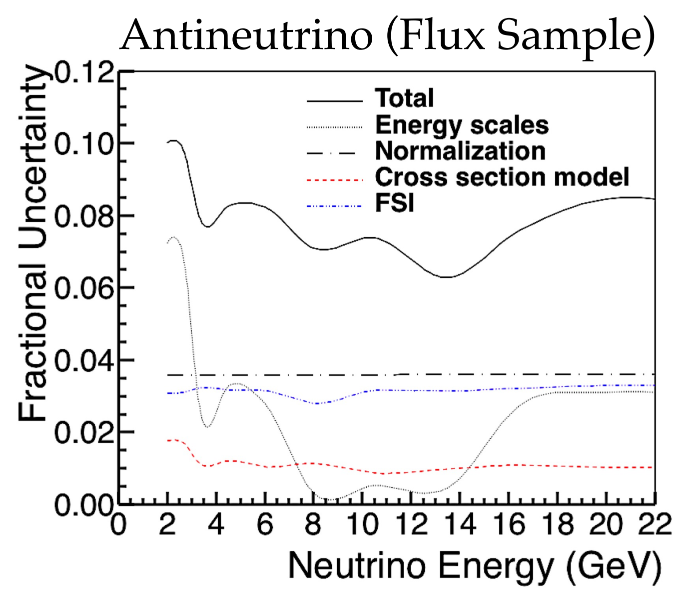
✤ Energy Scales
- Muon energy scale (~2-3 %)
- Hadron energy scales: Individual response uncertainty for each final state particle produce
- Saturation and cross talk

✤ Cross section Models
- GENIE recommends set of parameter variation for systematic uncertainties for tuned model components in hybrid GENIE

✤ Final State Interactions (~3.5 %)

✤ Normalization uncertainties (~3.6 %)
- Precision of in NOMAD data in the normalization region





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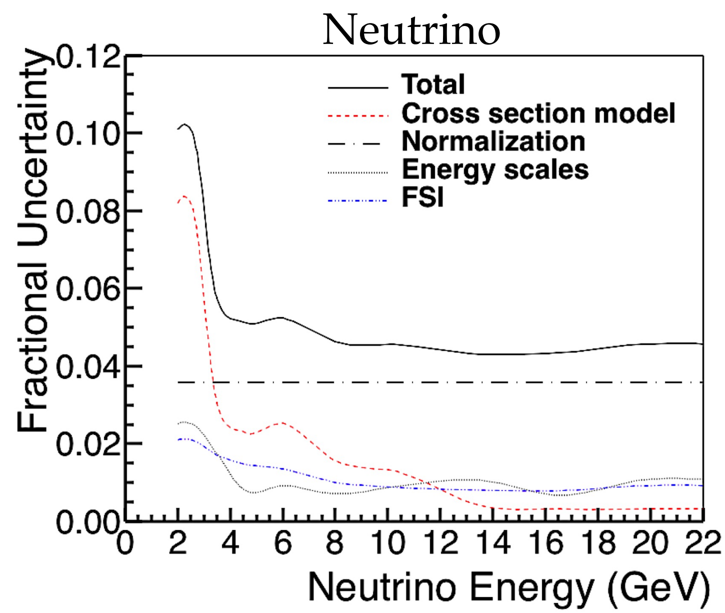
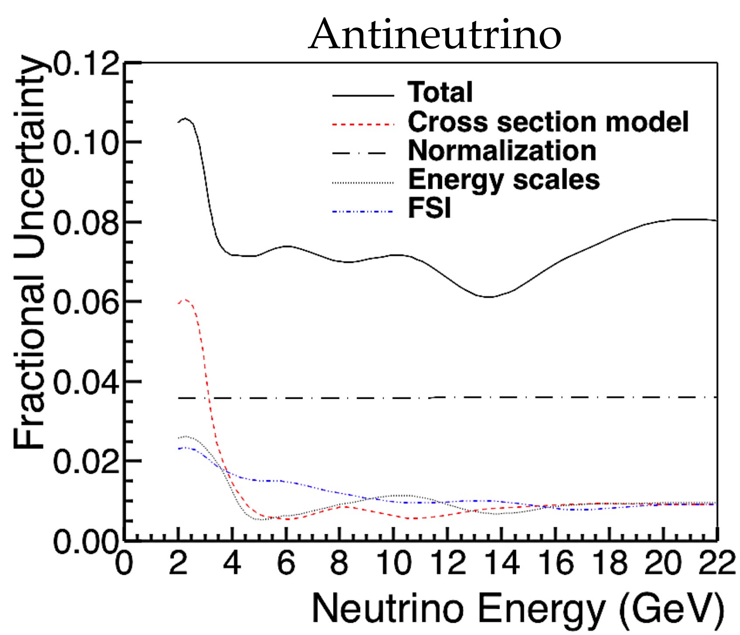
Systematics Uncertainties on CC Inclusive Cross Section





- Many systematic effects are similar in flux and cross section samples and partially cancel in the total cross section
- Uncertainty from cross section model dominates at low energy, normalization at higher energies
- Similar cross section model uncertainty for neutrino and anti neutrino sample

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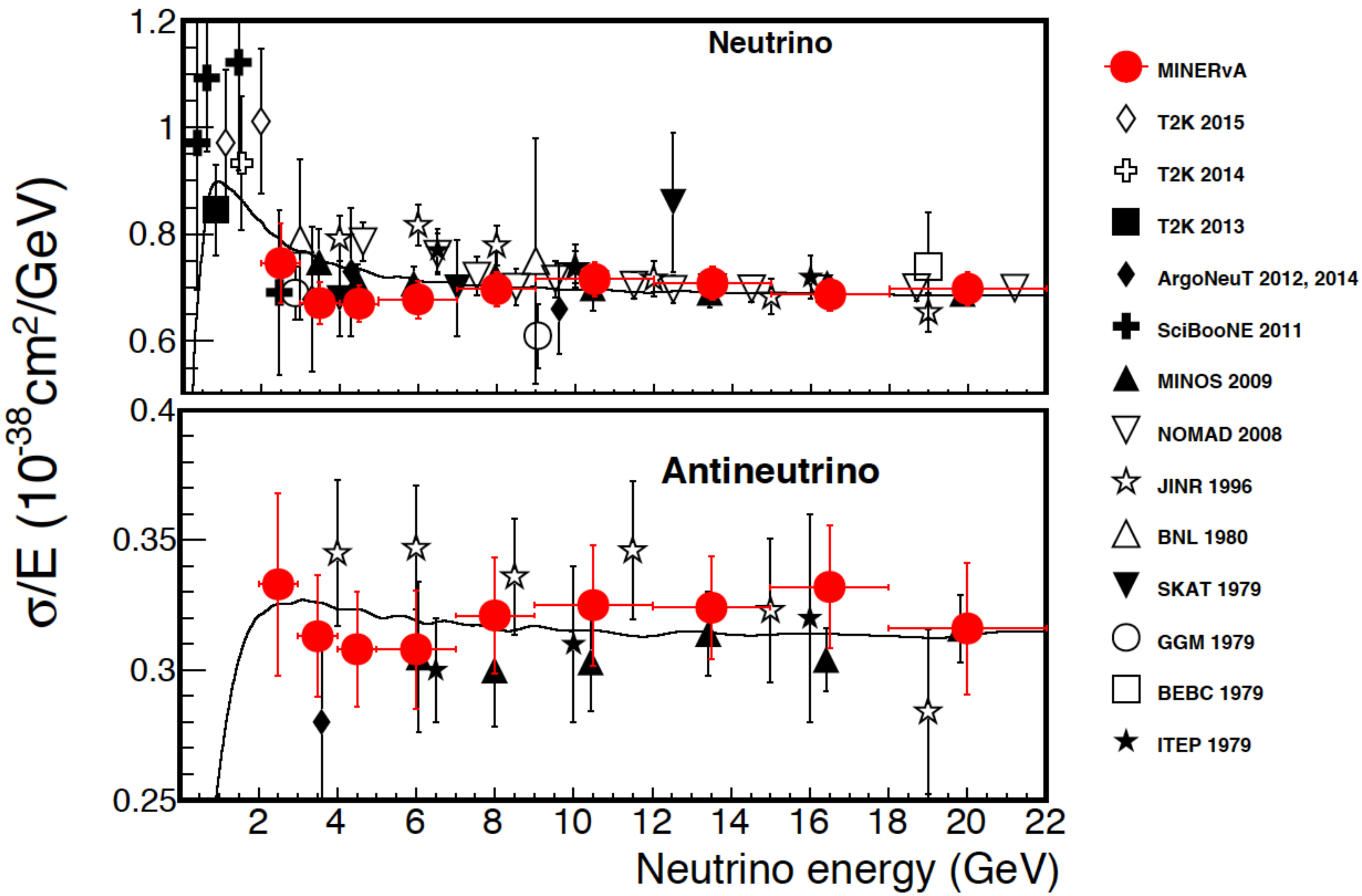
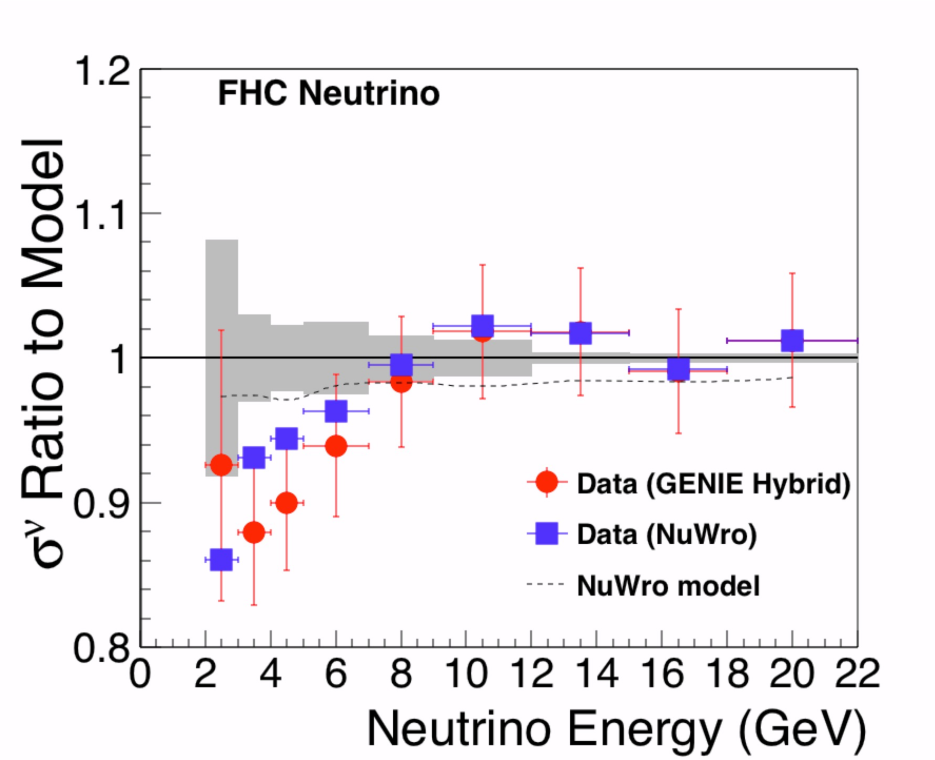
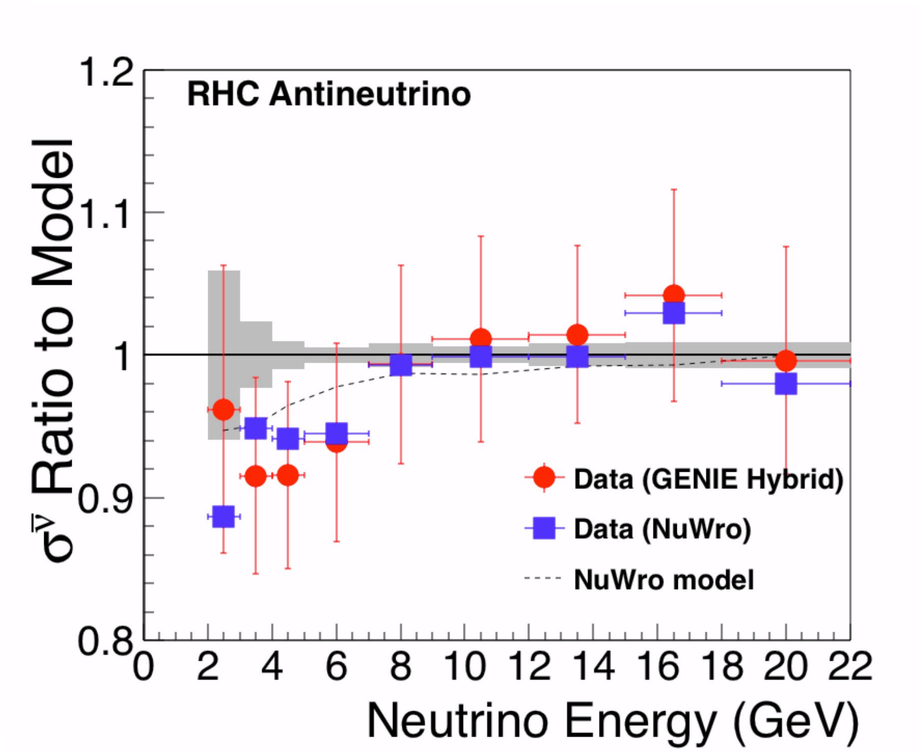
CC Inclusive Cross Section



Neutrino (top) and antineutrino (bottom) cross sections from MINERvA overlaid with world data

CC Inclusive Cross Section: Model Comparison





Data points extracted using GENIE hybrid model correction favor lower total cross section

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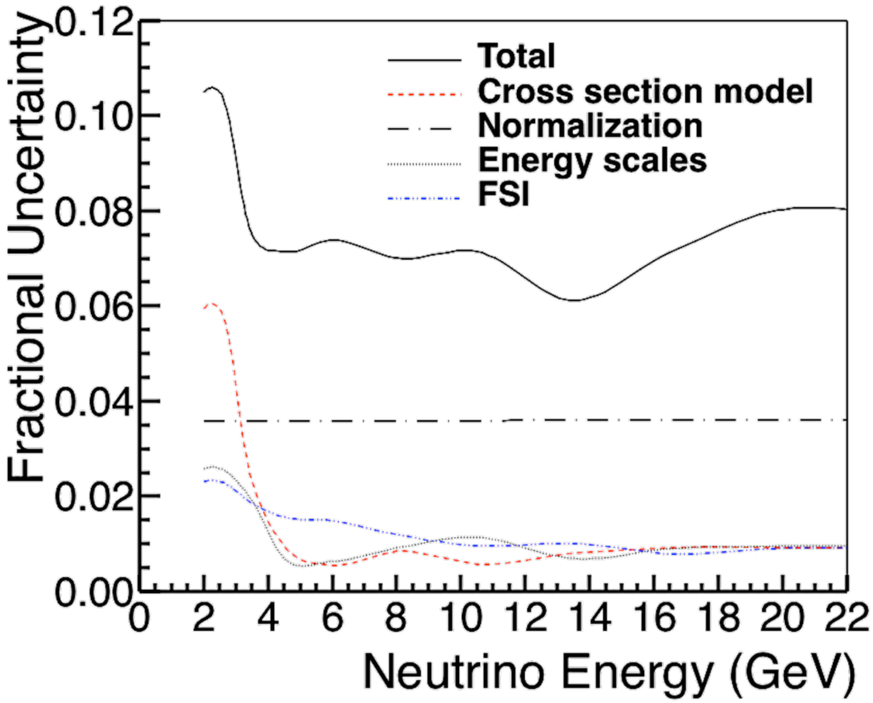
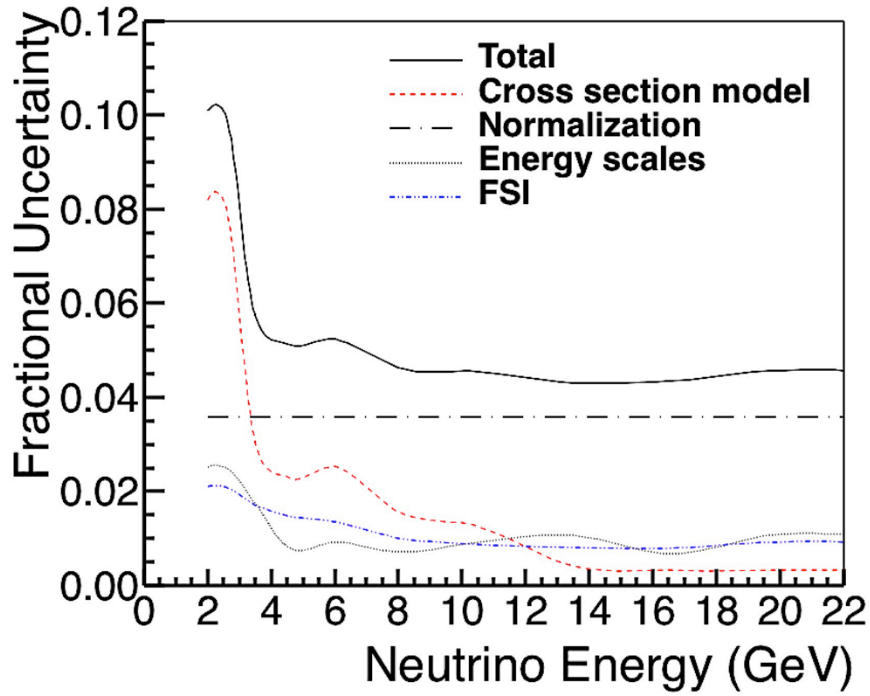
Systematic Uncertainties on Cross Sections

Uncertainties on Neutrino Cross section



Uncertainties on Antineutrino Cross section



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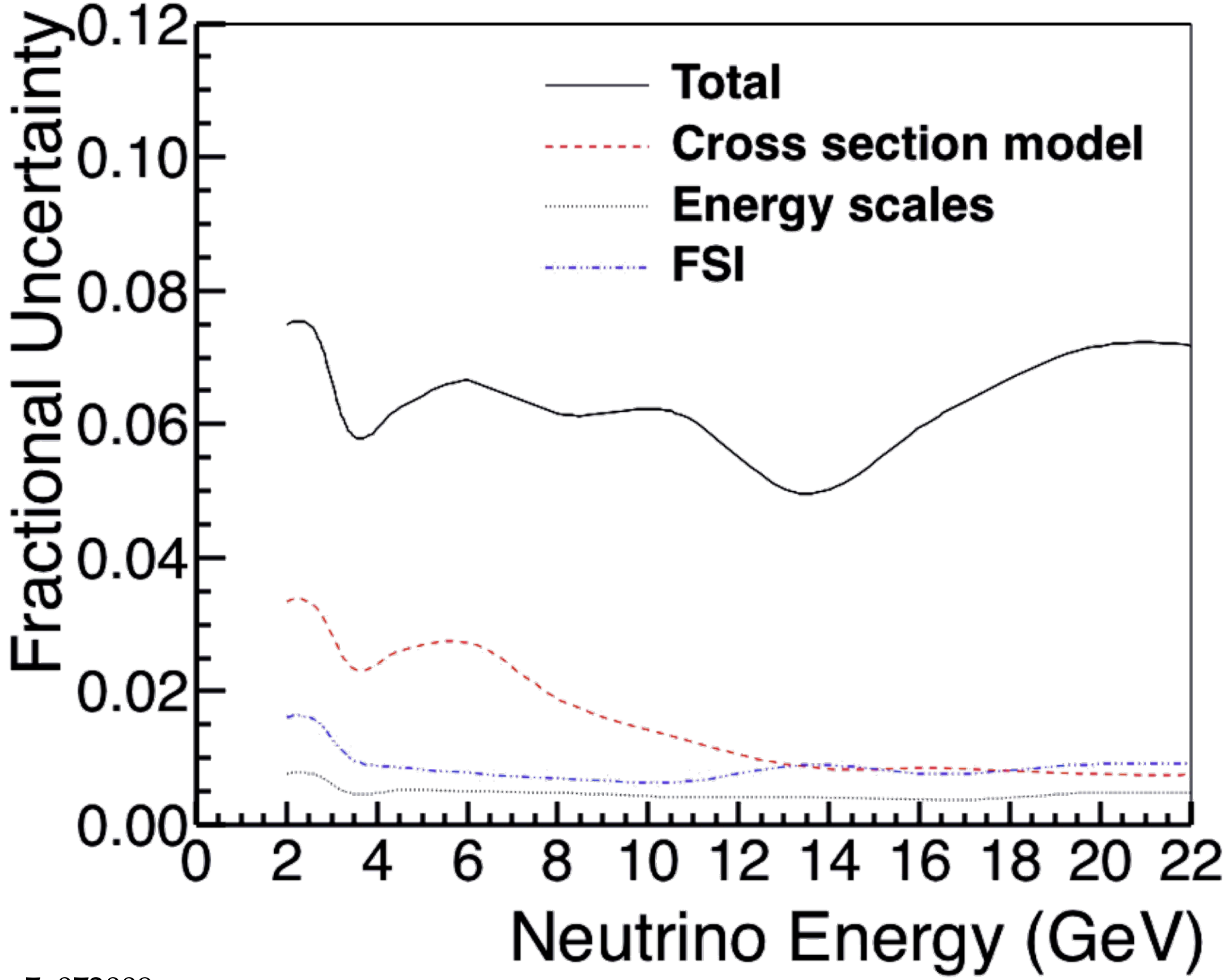
Systematic Uncertainties on Cross Section Ratio

Common uncertainties cancel!



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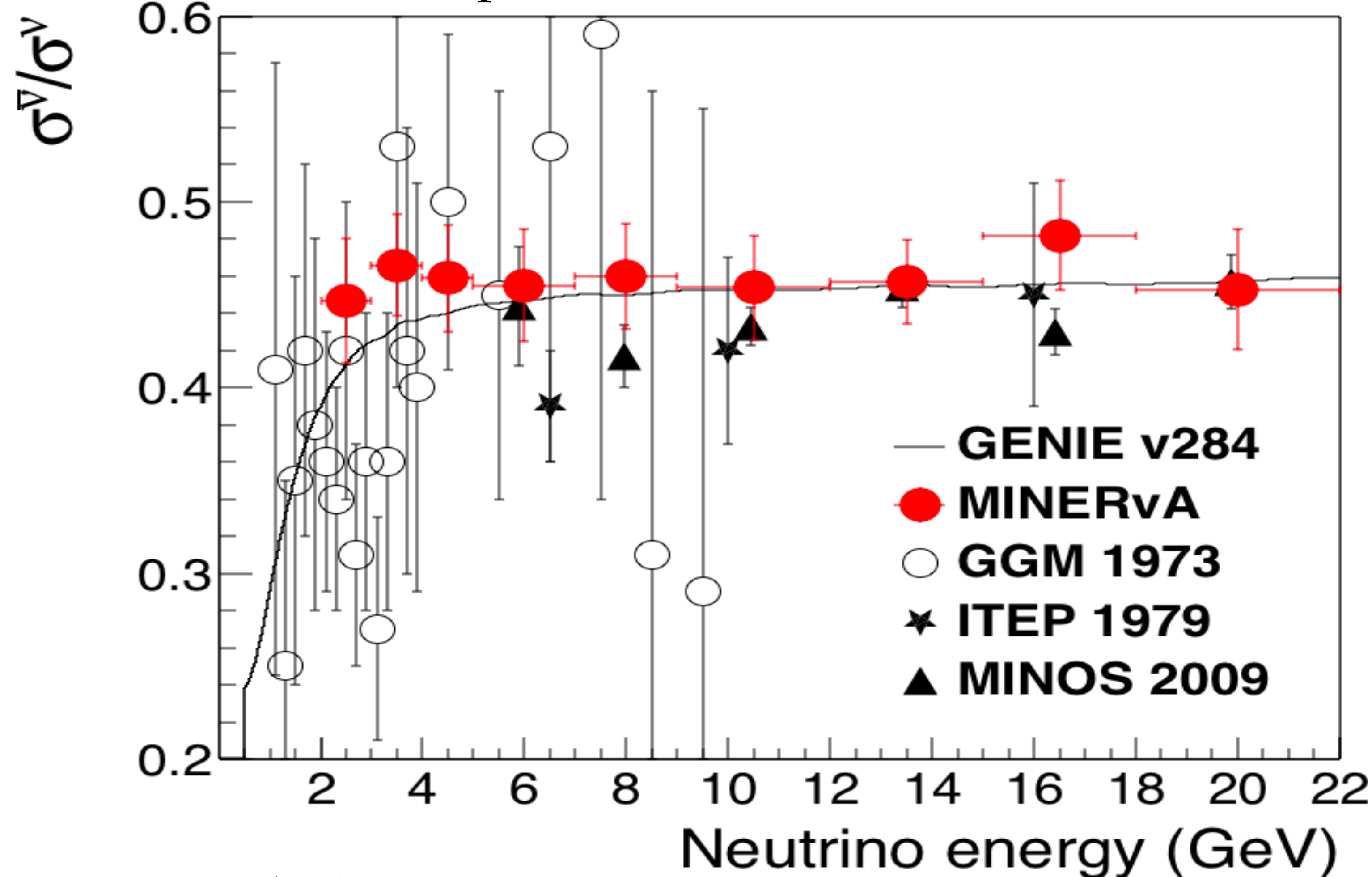
Antineutrino / Neutrino Cross section Ratio

Most precise ratio below 6 GeV !



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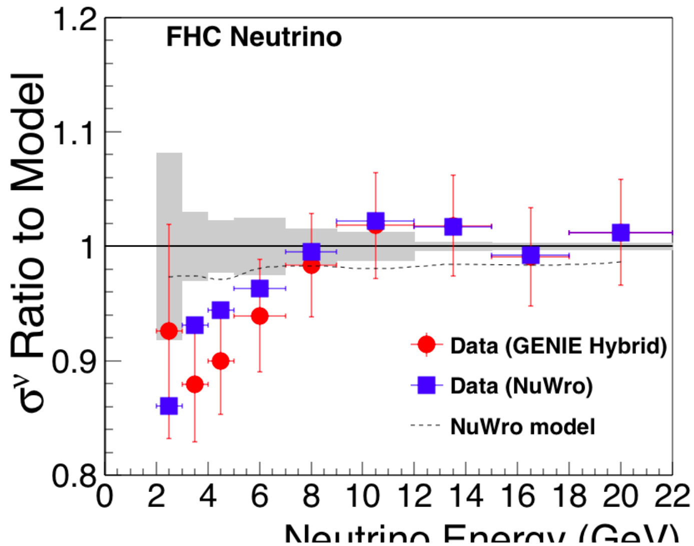
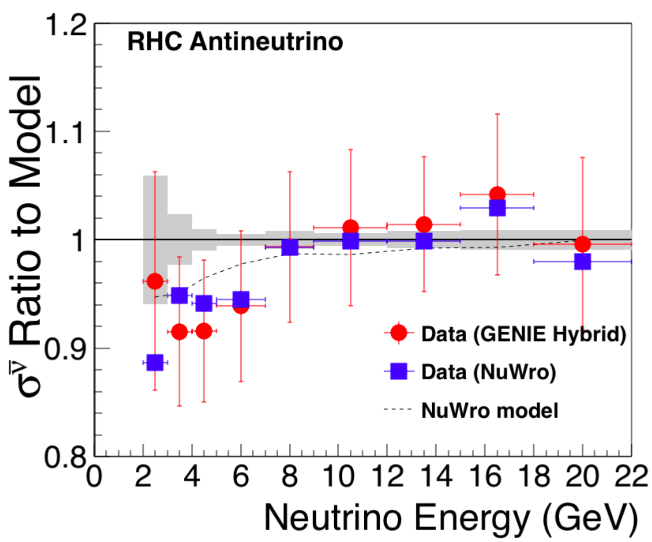
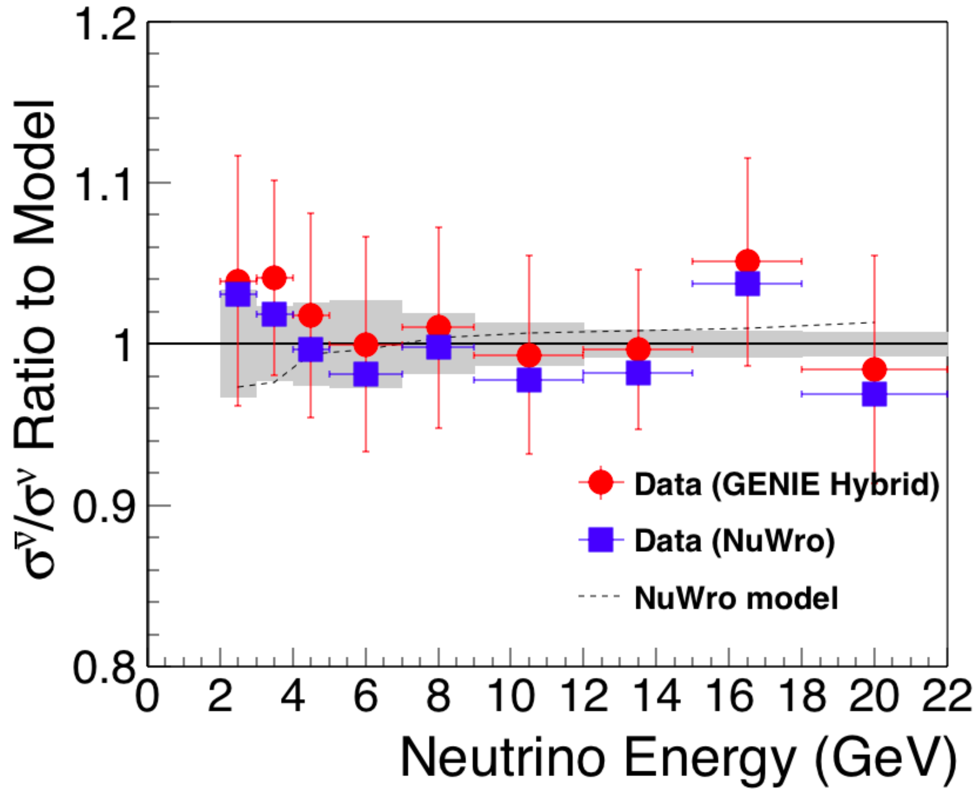
Antineutrino / Neutrino Cross Section Ratio: Model Comparison







The shape of the ratio between antineutrino to neutrino is not in agreement with the models DUNE energy regime

L. Ren et al., Phys.Rev. D95 (2017) no.7, 072009.
L. Ren, PhD Thesis, University of Pittsburgh, 2017.

Summary

- MINERvA utilized low-nu flux technique to extract antineutrino and neutrino cross section, and their ratios
- Our measurement with precision in the range ~5-7 % represents a large improvement over previous measurements that region
- MINERvA data extends reach for antineutrino data to lower energies
- Our data provides first precise measurement of anti-neutrino to neutrino cross section ratio in below 6 GeV