Measurement of Antineutrino to Neutrino Charged-current Interaction Cross Section Ratio in MINERvA

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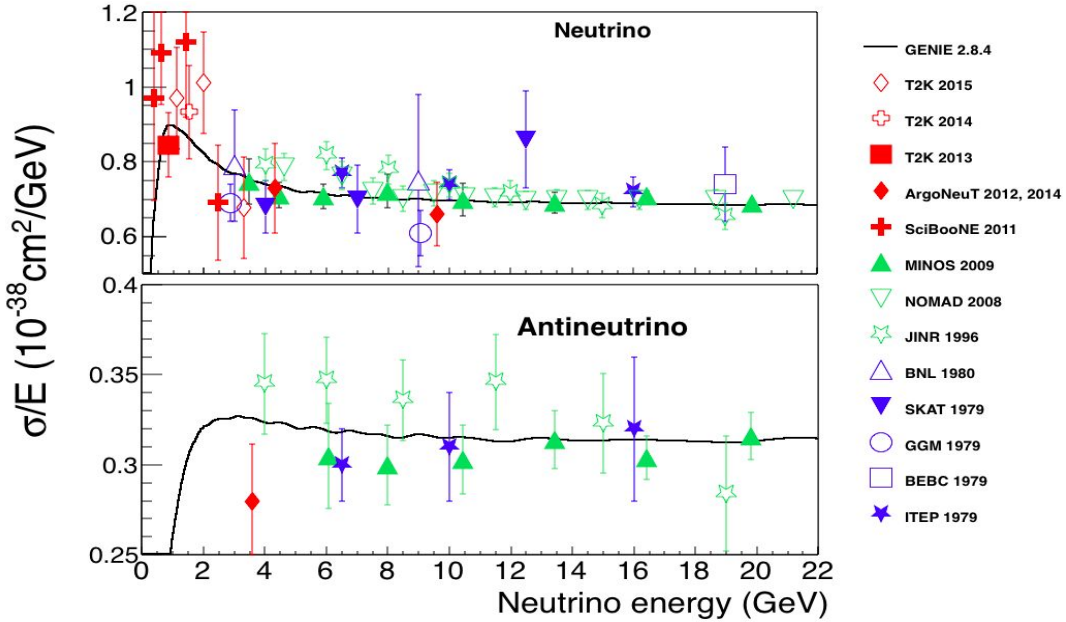
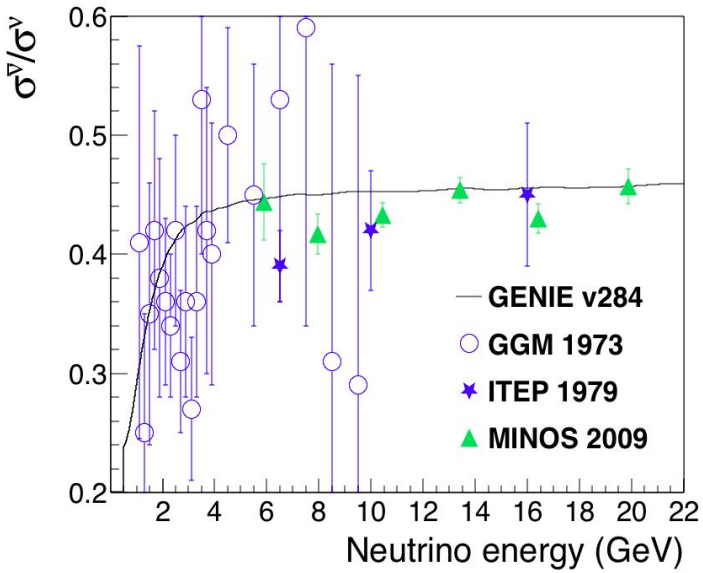
Outline

- Motivation
- Low-ν Method
- Systematic Uncertainty
- Results
- Conclusion

Motivation

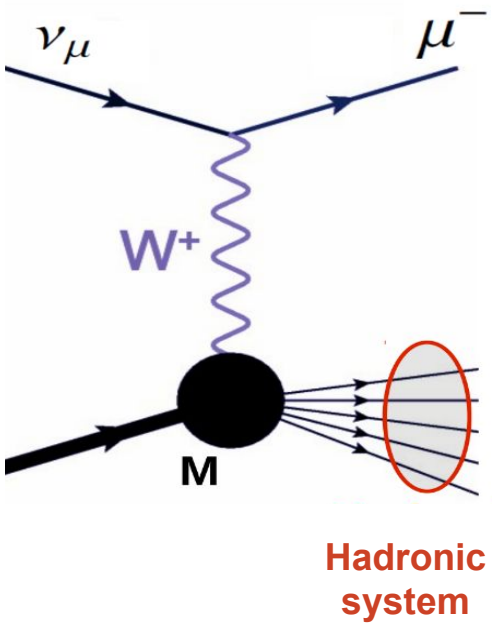
- Future long-baseline oscillation experiments measure oscillation parameters and CP phase using neutrino and antineutrino beams below 10 GeV
- CP asymmetry $A_{cp} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})}$ is sensitive to the antineutrino to neutrino cross section ratio





Low-ν Method

- Relies on the information from hadron energy $\boxed{\nu = E_{Had} = E_\nu - E_\mu}$
- $\frac{d\sigma^{\nu,\bar{\nu}}}{d\nu} = A(1 + \frac{B^{\nu,\bar{\nu}}}{A}\frac{\nu}{E} - \frac{C^{\nu,\bar{\nu}}}{A}\frac{\nu^2}{2E^2})$
- In the limit $\frac{\nu}{E} \to 0$
  - Cross sections are independent of neutrino energy
  - Neutrino and antineutrino are almost identical
  - Small ν/E dependent correction
  - Flux normalized with external (neutrino) world data.



Low-ν Method

$$\sigma_{CC}^{\nu(\bar{\nu})}(E) \propto \mathcal{R}^{\nu(\bar{\nu})} \times S^{\nu(\bar{\nu})}(\nu_0, E) \times A_{CC}^{\nu(\bar{\nu}),\mathrm{KIN}}(E)$$

Corrected event rate

Low-ν correction

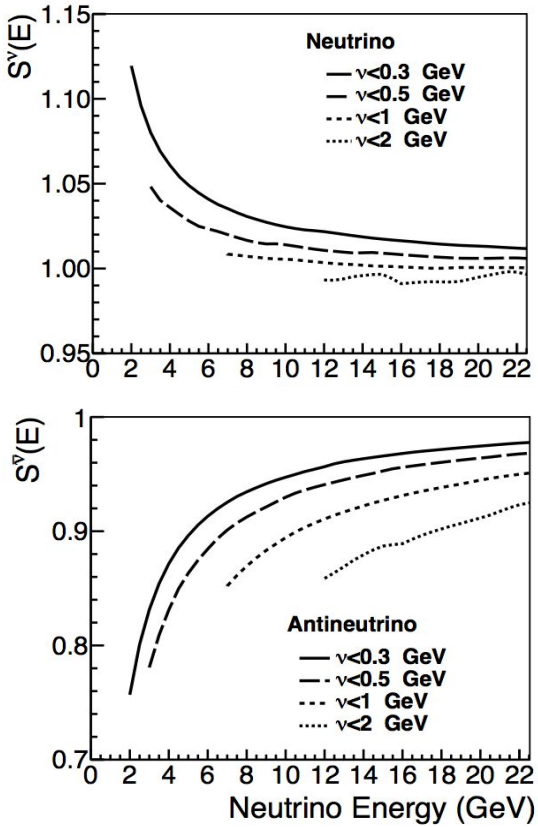
Kinematic correction

- **Kinematic correction** accounts for low muon energy and wide muon angle region where there is no acceptance
- **Low-ν correction** accounts for B and C terms in $\frac{d\sigma^{\nu,\bar{\nu}}}{d\nu}$

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

- Antineutrino and neutrino use the same **normalization constant**, except for a term due to quark mixing

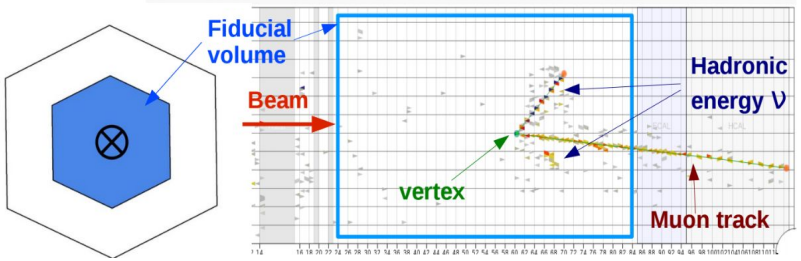
$$R_{CC}(E) = \frac{\sigma_{CC}^{\bar{\nu}}(E)}{\sigma_{CC}^{\nu}(E)} = \frac{\mathcal{R}^{\bar{\nu}}}{\mathcal{R}^{\nu}} \left(\frac{A_{CC}^{\bar{\nu},KIN}(E) \times S^{\bar{\nu}}(\nu_0, E) \times \boxed{H^{\bar{\nu}}(\nu_0)}}{A_{CC}^{\nu,KIN}(E) \times S^{\nu}(\nu_0, E) \times \boxed{H^{\nu}(\nu_0)}} \right)$$

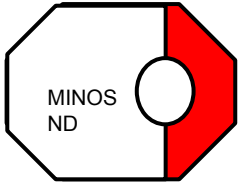


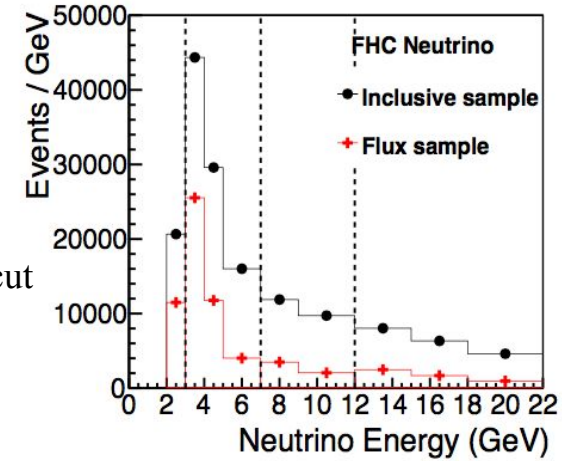
Charged-current Event Selection

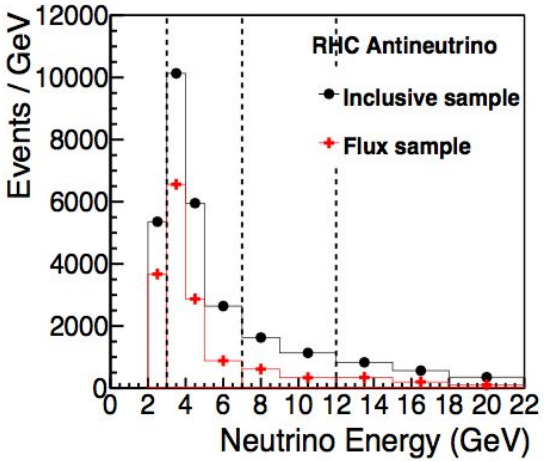
- Low Energy (LE) data
  - Forward Horn Current (FHC)
  - Reverse Horn Current (RHC)
- Inclusive sample
  - Events with a vertex in fiducial volume and a muon matched in MINOS near detector
  - Kinematic cuts
    - E_μ >1.8 GeV
    - θ_μ < 0.35 rads
- Flux sample
  - Extra maximum hadron energy cut

E Range (GeV)	ν_o (GeV)
2-3	0.3
3-7	0.5
7-12	1.0
>12	2.0









Systematic Uncertainty

- Normalization: precision of NOMAD[1] measurements in normalization region (3.58%)
- Model uncertainty (GENIE-Hybrid)
  - GENIE recommended 26 parameter variations
    - Rein-Seghal, Bodek-Yang, FSI, etc.
  - Valencia 2p2h model
  - Random Phase approximation (RPA)
- Reconstruction
  - Muon energy scale
    - Muon momentum reconstruction
    - Detector mass and energy loss per length
  - Hadron energy scale
    - Detector response of final state particles

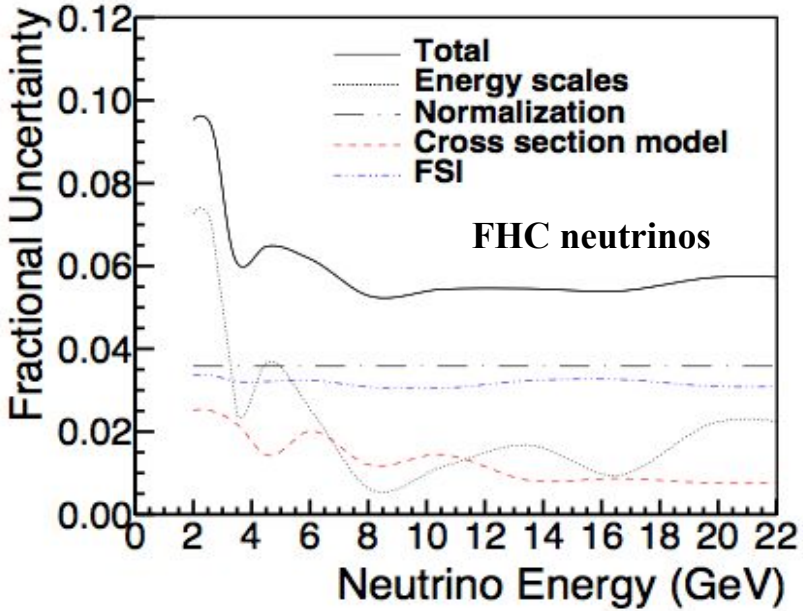
Error Source	Error
MINOS Range	2.%
MINOS Curvature ($p_\mu < 1GeV$)	2.5%
MINOS Curvature ($p_\mu > 1GeV$)	0.6%
MINERvA $\frac{dE}{dx}$ (scintillator)	30 MeV
MINERvA $\frac{dE}{dx}$ (C, Fe, Pb)	40 MeV
MINERvA mass (scintillator)	11 MeV
MINERvA mass (C, Fe, Pb)	17 MeV

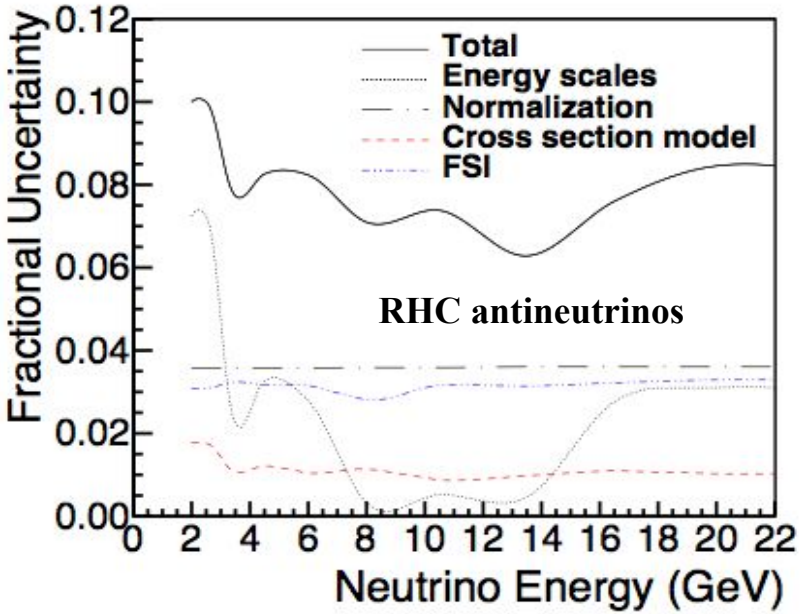
Energy Source	Uncertainty
Proton	3.5%
Neutron (KE <50 MeV)	25%
Neutron (50 <KE <150 MeV)	10%
Neutron (KE >150 MeV)	20%
Muon	2.4%
γ, π^0, $e^\pm$	3%
$\pi^\pm$, Kaon	5%
Cross talk	20%
Other	20 %

1. *NOMAD Collaboration (Wu, Q. et al.) Phys.Lett. B660 (2008) 19-25*

Systematic Uncertainty on Fluxes

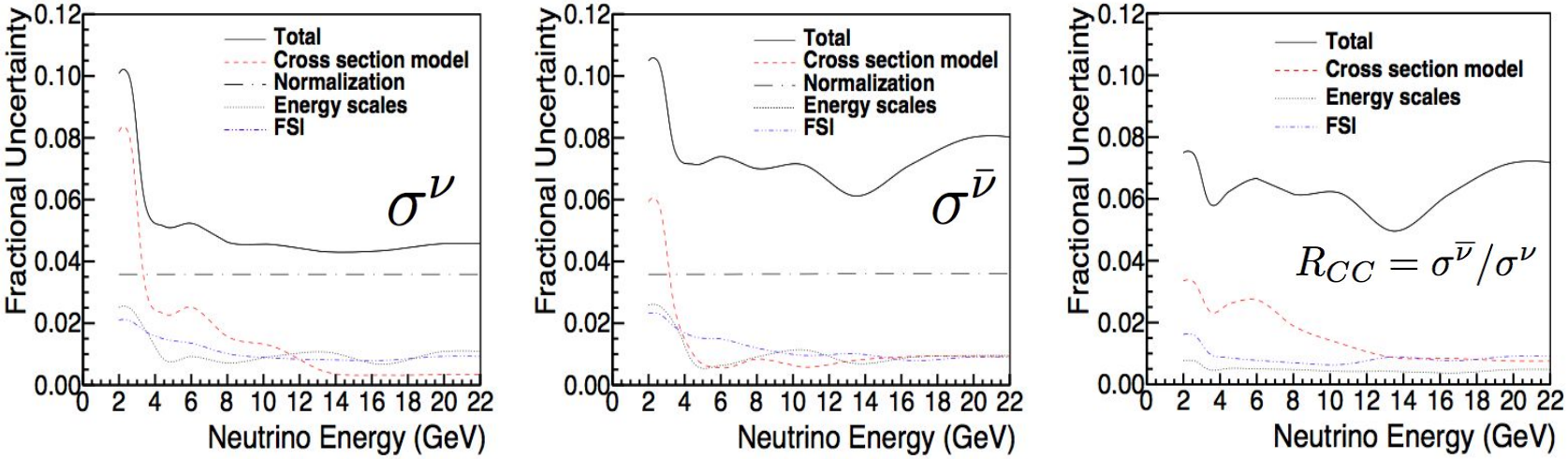
- Dominated by energy scales at low energy
- Dominated by external normalization at high energy
- Larger statistical uncertainty for antineutrinos





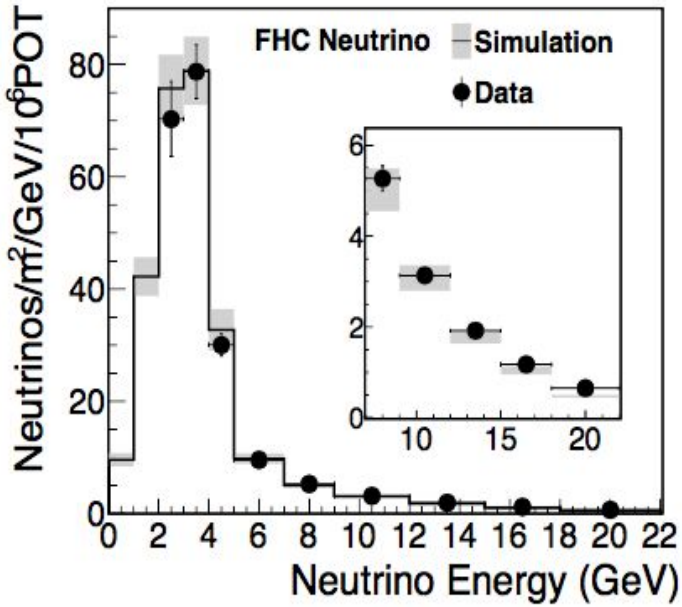
Systematic Uncertainty on Cross Sections and the Ratio

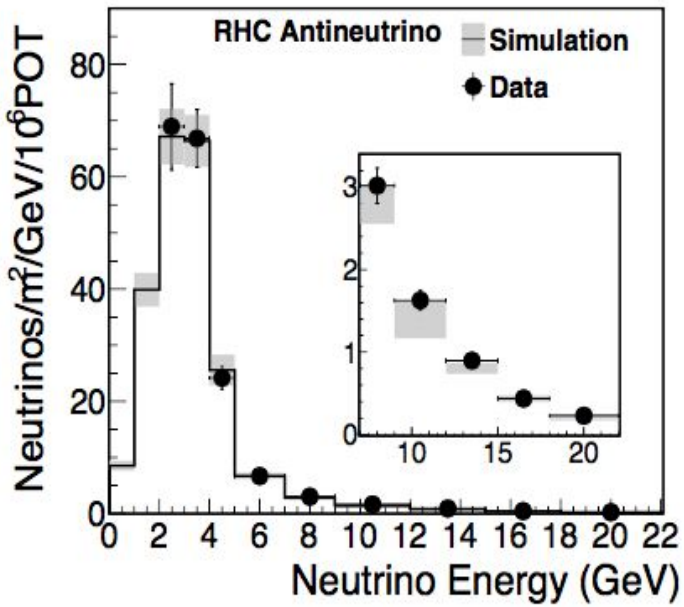
- Cross sections
  - Common systematics of inclusive and flux samples cancel for the cross sections (e.g., energy scales)
  - Cross section model uncertainty dominates at low energy, normalization dominates at high energy
- Ratio
  - Common systematics of neutrino and antineutrino cross sections partially cancel for the ratio (e.g. normalization and cross section model uncertainty)
  - Statistical uncertainty dominates



Fluxes

- Extracted low-ν fluxes comparing with input MC fluxes (hadron production model)
- Low-ν fluxes have a factor of 1.5-1.9 improvement of uncertainties

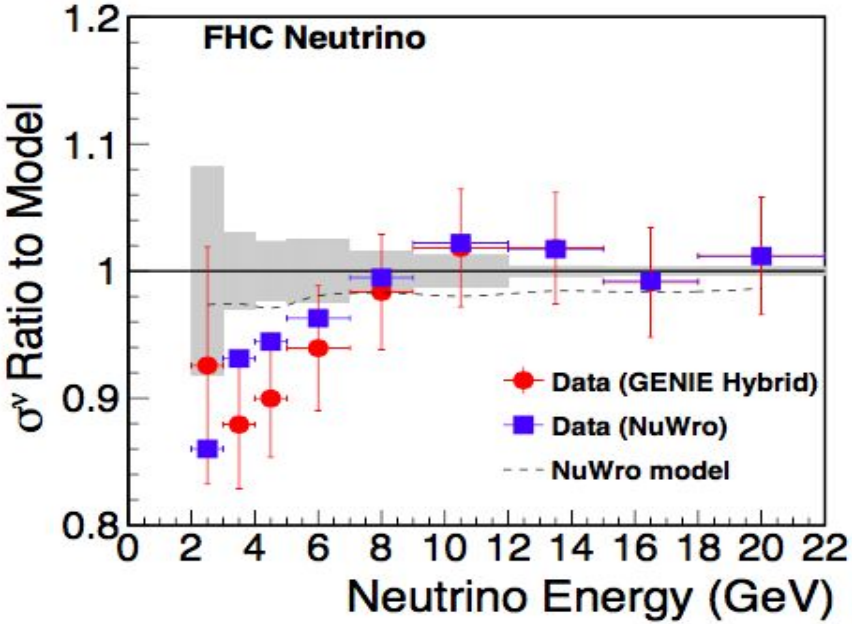


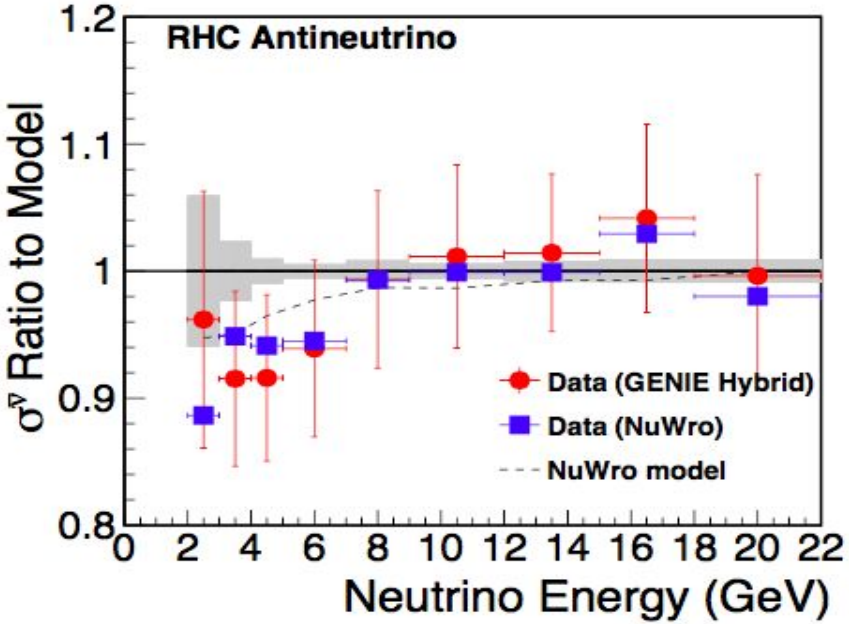


Cross Sections: Data vs Model

- The primary results are ~2σ below the model at low energy
- Difference between two results is due to different cross section models and different kinematic modeling at low energy

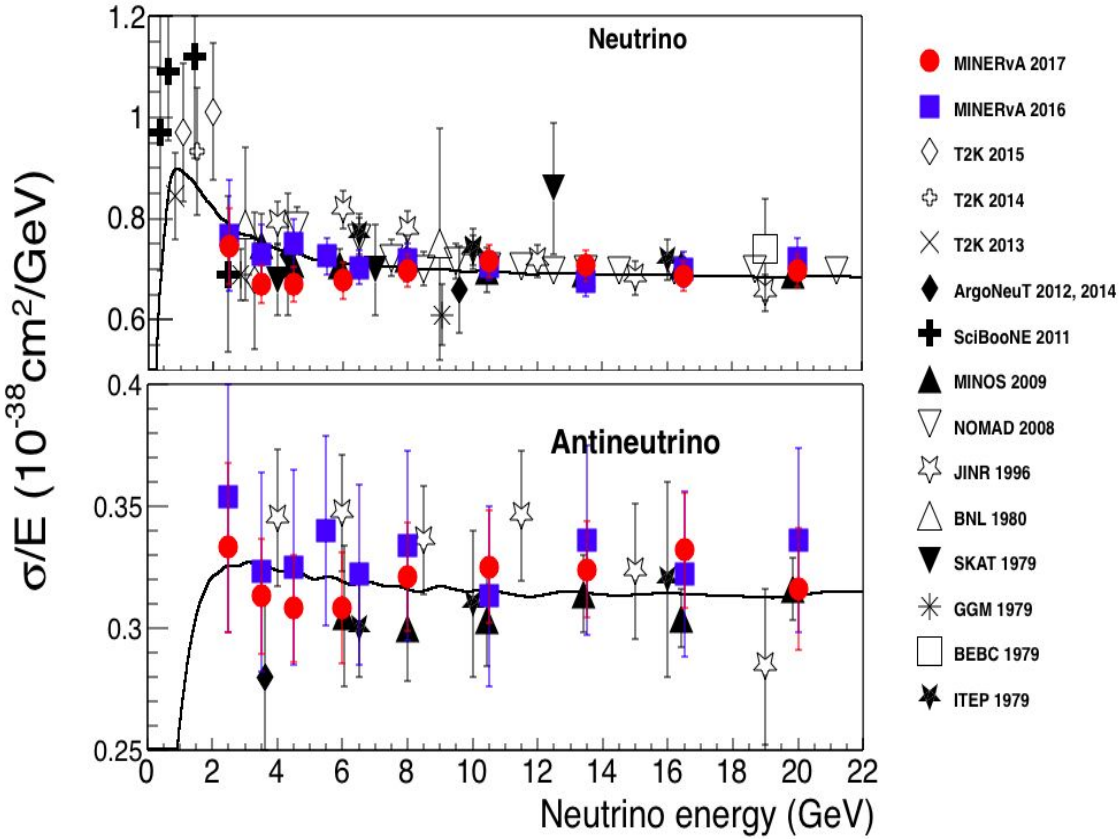
Primary: GENIE-hybrid
Alternative: NuWro





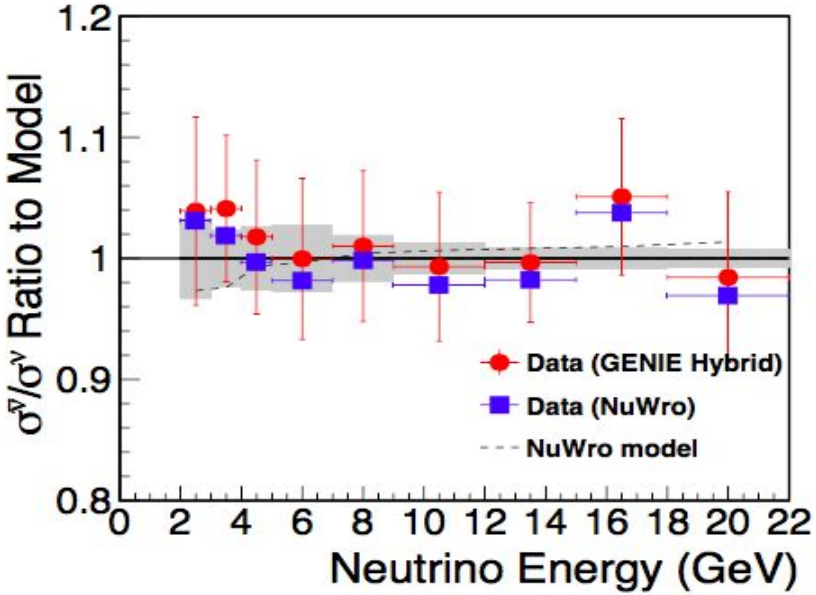
Cross Sections: World Data

- Measured cross sections comparing with GENIE 2.8.4 in the energy range 2-22 GeV
- Neutrino cross section normalized to NOMAD in 12-22 GeV, antineutrino cross section normalization is related to neutrino
- Most precise measurement of antineutrino cross section below 6 GeV



Cross Section Ratio: Data vs Model

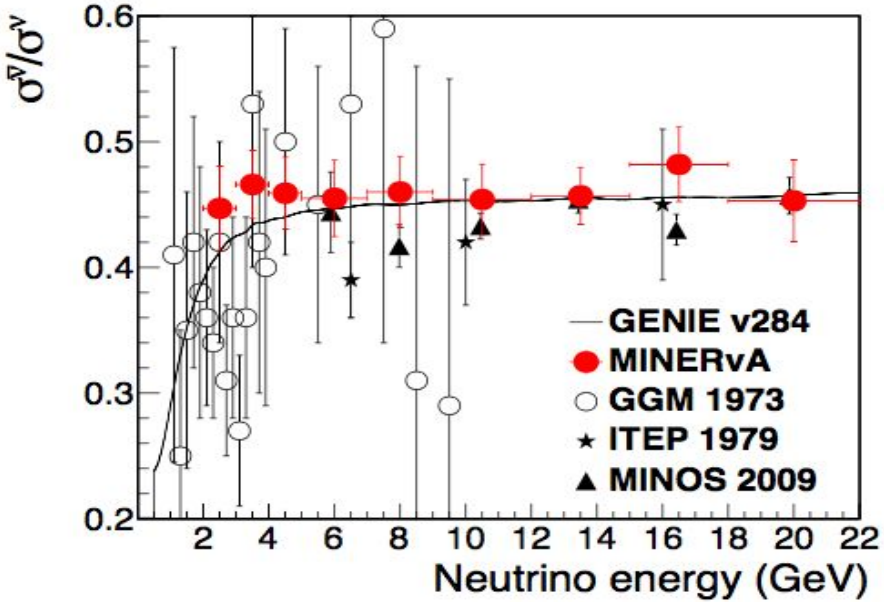
- Results are above the model ($< 1\sigma$) at low energy
- The difference between two results are smaller than cross sections due to cancellation between neutrino and antineutrino cross sections
- NuWro result is below GENIE-Hybrid result everywhere



Primary: GENIE-hybrid
Alternative: NuWro

Cross Section Ratio: World Data

- Antineutrino to neutrino CC inclusive cross section ratio $R_{CC} = \sigma^{\bar{\nu}}/\sigma^{\nu}$
- First precise measurement below 6 GeV
  - Many systematic uncertainties cancel in the ratio
  - The precision reaches ~5%
  - Can be improved by increasing antineutrino sample



Conclusions

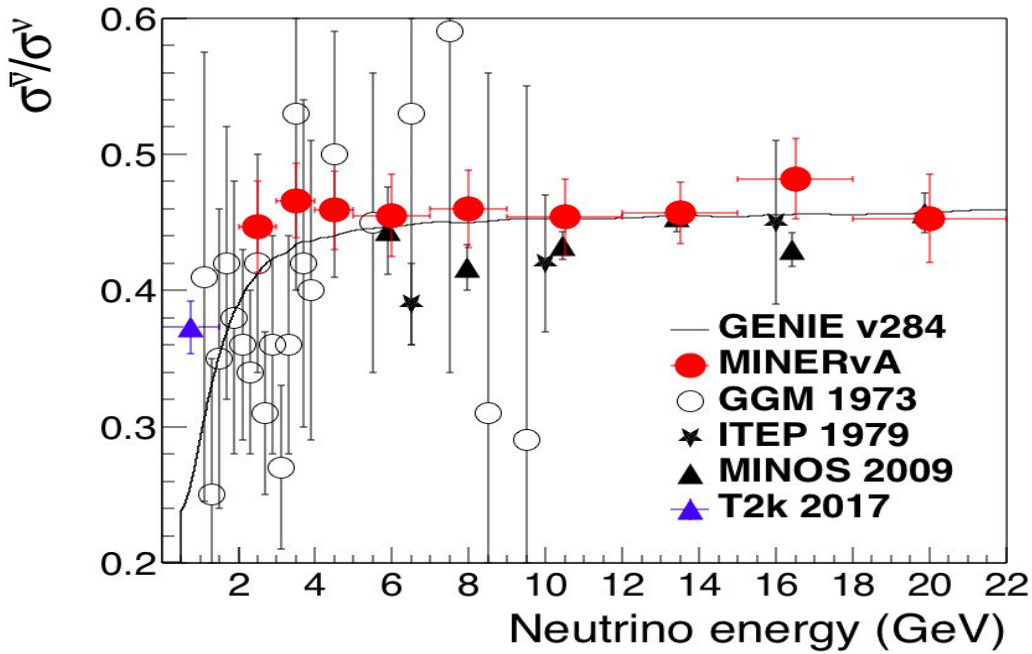
- Measured neutrino and antineutrino fluxes, cross sections and the antineutrino to neutrino cross section ratio in the 2-22 GeV region
  - Fluxes: reasonable agreement with hadron production model
  - Neutrino cross section : ~10% below model at low energy, has the similar trend as world data
  - Antineutrino cross section and ratio : most precise measurement below 6 GeV, error dominated by statistics
- Feature of this measurement
  - Results with GENIE and NuWro model corrections
  - Allow correction from alternative models in the future

L. Ren et al. (MINERvA Collaboration), Phys.Rev. D95 (2017) no.7, 072009

Backup

T2K result

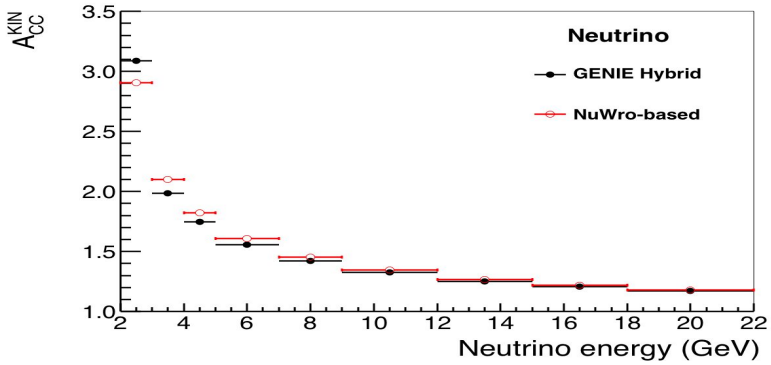
- T2K recently published CC Inclusive cross sections and the ratio below 1.5 GeV, https://arxiv.org/pdf/1706.04257.pdf
- Ratio: 0.373 ± 0.012(stat.) ± 0.015(syst.), 5% total uncertainty

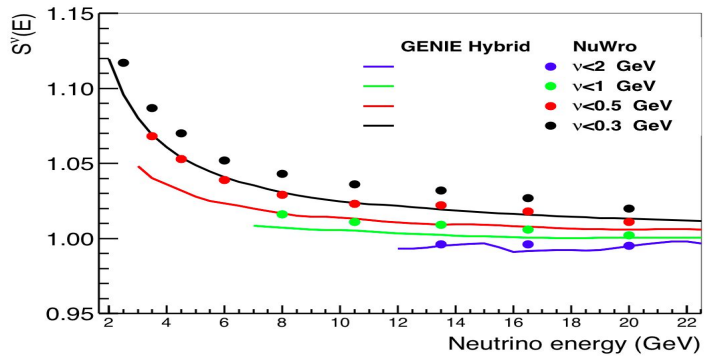


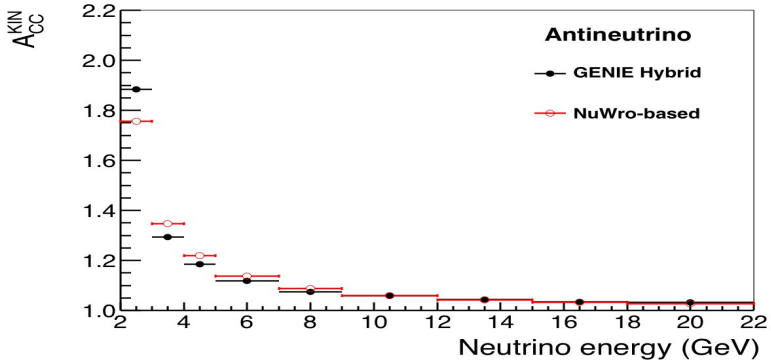
Model-dependence Corrections

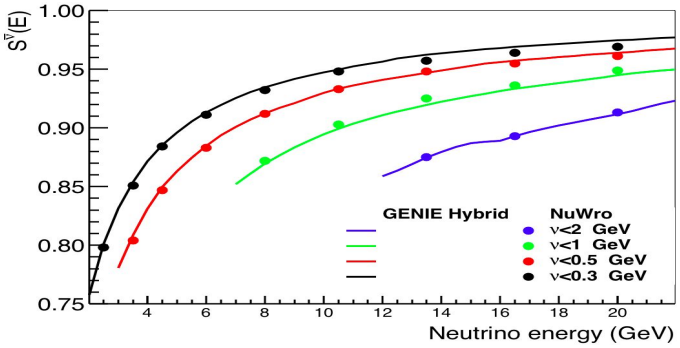
$$A^{\mathrm{KIN}} = \frac{N_{MC}^{true}(E_i)}{N_{MC}^{true}(E_i, E_\mu > E_{\mu min}, \theta_\mu < \theta_{\mu max})}$$

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









GENIE uncertainty

GENIE Knob name	Description	1 σ
MaRES	Ajust M_A in Rein-Seghal cross section	±20%
MvRES	Ajust M_v in Rein-Seghal cross section	±10%
Rvp1pi	1 pi production from νp non-resonant interactions	±50%
Rvn1pi	1 pi production from νn non-resonant interactions	±15%
Rvp2pi	2 pi production from νp non-resonant interactions	±50%
Rvn2pi	2 pi production from νn non-resonant interactions	±50%
VeCFFCCQEshape	Changes from BBBA to dipole	on or off
AhtBY	Bodek-Yang parameter A_{HT}	±25%
BhtBY	Bodek-Yang parameter B_{HT}	±25%
CV1uBY	Bodek-Yang parameter C_{V1u}	±30%
CV2uBY	Bodek-Yang parameter C_{V2u}	±40%

GENIE Knob name	Description	1 σ
MFP_N	mean free path for nucleons	±20%
FrCex_N	nucleon fates - charge exchange	±50%
FrElas_N	nucleon fates - elastic	±30%
Frinel_N	nucleon fates - inelastic	±40%
FrAbs_N	nucleon fates - absorption	±20%
FrPiProd_N	nucleon fates - pion production	±20%
MFP_pi	mean free path for pions	±20%
FrCEx_pi	pion fates - charge exchange	±50%
FrElas_pi	pion fates - elastic	±10%
Frinel_pi	pion fates - inelastic	±40%
FrAbs_pi	pion fates - absorption	±30%
FrPiProd_pi	pion fates - pion production	±20%

EFNUCR	Increase/decrease to nuclear size for low energy hadrons.
FZONE	Change formation time by 50%
Hadronization_Alt1	Change AGKY model to do a simple phase space decay of hadrons.