Measuring Neutrino Flux at Low Energies: The Low ν Method

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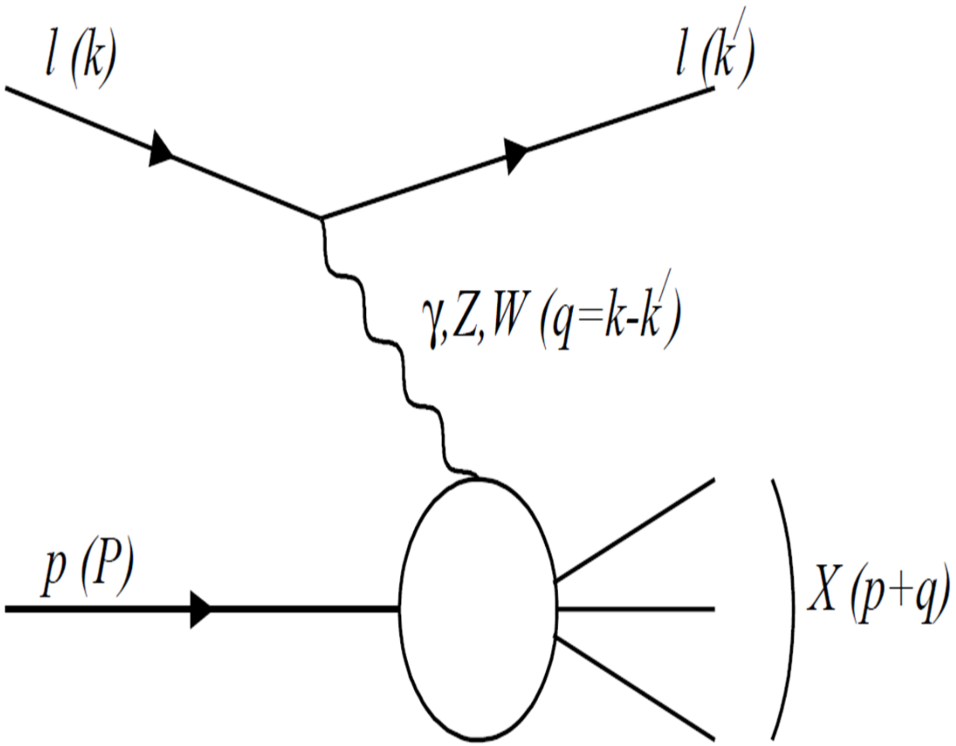
Why Do We Need to Determine the Flux at Low Energies?

- Total cross section should be well understood for neutrino oscillation experiments such as T2K, NOvA and MINOS at 500 MeV – 3 GeV.
- MINERvA can investigate cross sections above 500 MeV.
- Flux uncertainty accounts for about 10% of the systematic uncertainty in $|\Delta m^2|$ [1] and in MINERvA.

The General Process



$$
\begin{aligned}
Q^2 &= -q^2 = -(k-k')^2 > 0, \\
s &= (P+k)^2, \\
W^2 &= (P+q)^2, \\
x &= \frac{Q^2}{2P\cdot q}, \\
y &= \frac{P\cdot q}{P\cdot k}, \\
\nu &= \frac{P\cdot q}{M}.
\end{aligned}
$$

$$\left(\upsilon = \frac{Q^2 + W^2 - M^2}{2M}\right)$$

Source:
Yang, Un Ki. «A Measurement of differential cross-sections in charged current neutrino interactions on iron and a global structure functions analysis.» FERMILAB-THESIS-2001-09, UMI-99-98273.3-4 (2001).

Cross Section Equation and Definitions

$$\frac{d\sigma^{ud}}{dQ^2 d\nu} = S_{cos}\frac{1}{2E^2}\mathcal{W}_1\left[Q^2 + m_\mu^2\right]$$

$$+S_{cos}\mathcal{W}_2\left[(1-\frac{\nu}{E}) - \frac{(Q^2+m_\mu^2)}{4E^2}\right]$$

$$+S_{cos}\mathcal{W}_3\left[\frac{Q^2}{2ME} - \frac{\nu}{4E}\frac{Q^2+m_\mu^2}{ME}\right]$$

$$+S_{cos}\mathcal{W}_4\left[m_\mu^2\frac{(Q^2+m_\mu^2)}{4M^2E^2}\right]$$

$$-S_{cos}\mathcal{W}_5\left[\frac{m_\mu^2}{ME}\right]$$

$$\left(\upsilon = \frac{Q^2 + W^2 - M^2}{2M}\right)$$

$$\sigma_{tot}(E) = \sigma_{W_2}(\infty)\,[f_C]$$

$$f_C = [f_{W2} + f_2 + f_1 + f_3 + f_4 + f_5]$$

$$f_{W2} = \frac{\sigma_{W2}}{\sigma_{W_2}(\infty)}(\approx 1)$$

$$f_2 = \frac{\sigma_2}{\sigma_{W_2}(\infty)}(= kinematic\ correction)$$

$$f_1 = \frac{\sigma_1}{\sigma_{W_2}(\infty)}(= important)$$

$$f_3 = \frac{\sigma_3}{\sigma_{W_2}(\infty)}(= important)$$

$$f_4 = \frac{\sigma_4}{\sigma_{W_2}(\infty)}(= very\ small)$$

$$f_5 = \frac{\sigma_4}{\sigma_{W_2}(\infty))}(= very\ small)$$

The Low ν Method for High Energies

- At high E, cross section for DIS dominates.

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

Multiply both sides by flux →

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

As ν→0, $\frac{dN}{d\nu} \approx \phi A$

The Low ν Method for High Energies

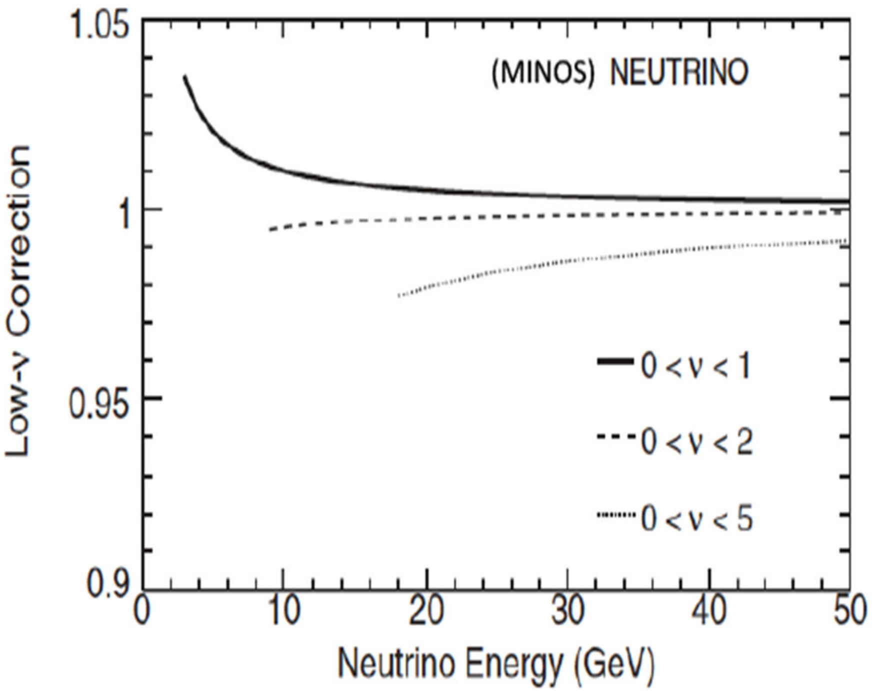
$$f_{C:\nu<\nu_{max}}(E) := \frac{\sigma(E, \nu < \nu_{max})}{\sigma(E \to \infty, \nu < \nu_{max})}$$

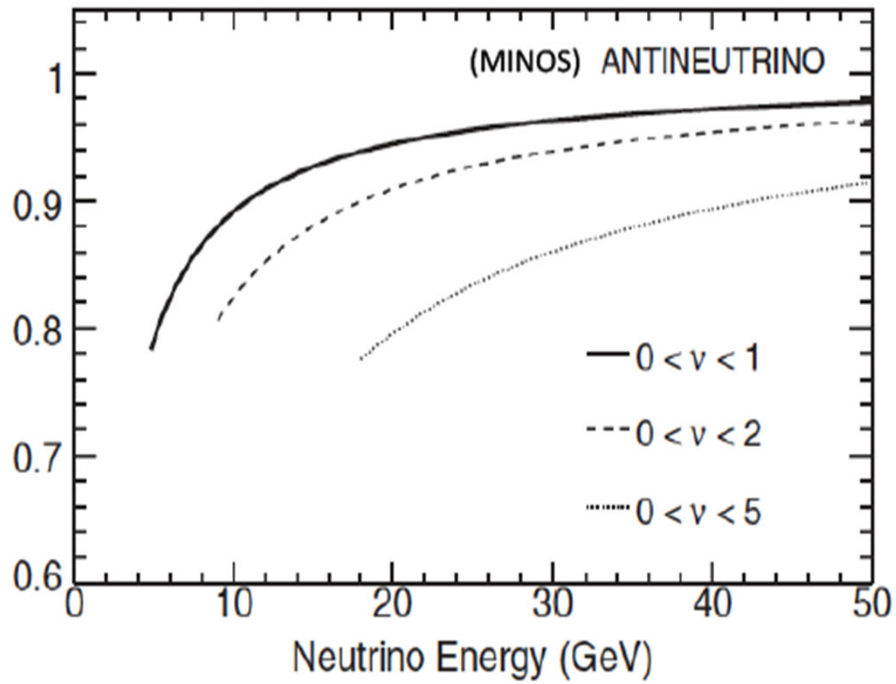
$$\phi(E) = \frac{\int_{\nu_{min}(E)}^{\nu_{max}} \frac{dN(E)}{d\nu} d\nu}{f_C(E) * A(E)}$$

ν_{min} is known from kinematics, but what determines ν_{max}?

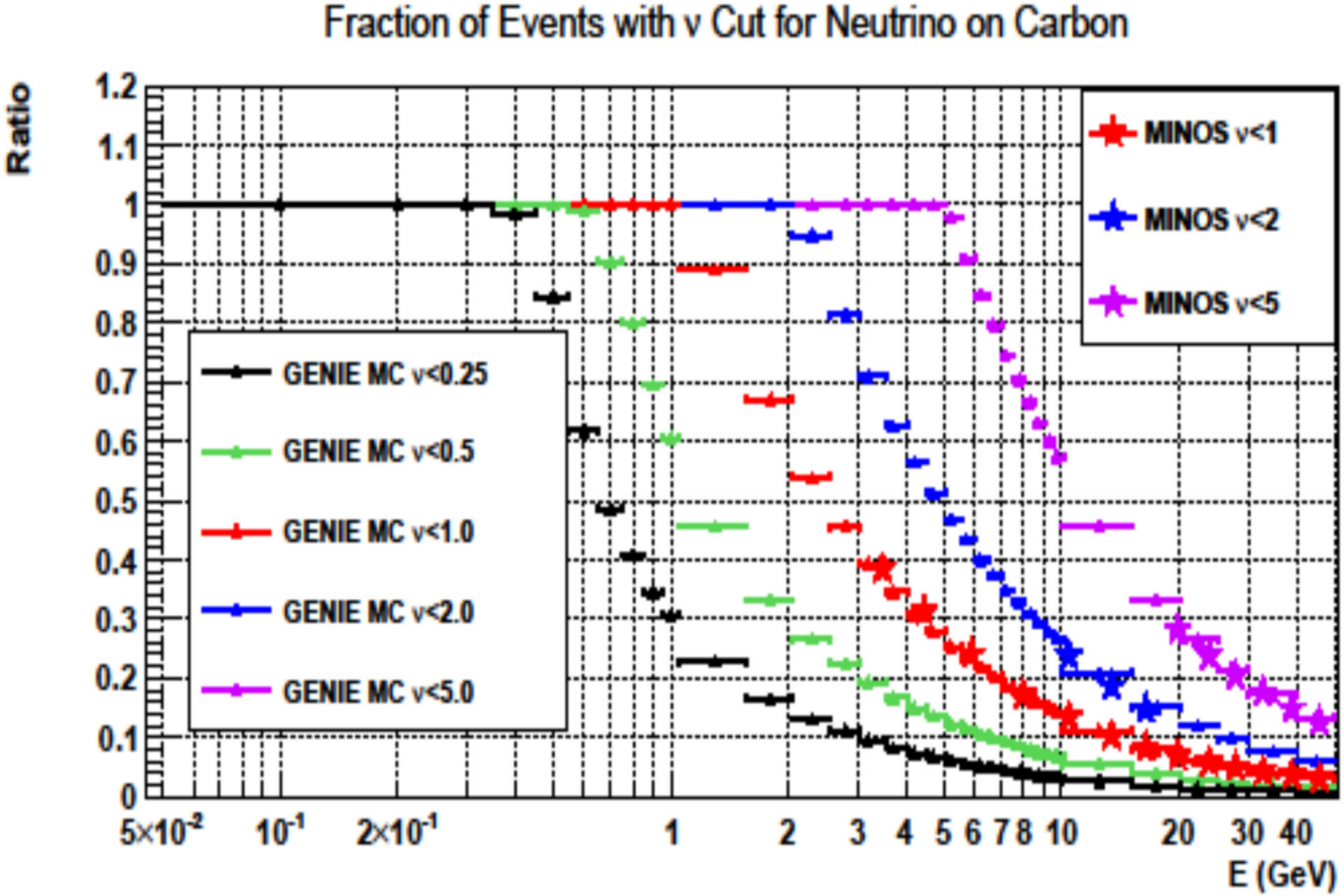
Criteria

- The MINOS Collaboration suggested the number of low ν events should not exceed 60% of the total cross section
- However, this number should also be statistically significant.
- Hence, MINOS used ν<1 GeV for E>3 GeV for neutrinos and E>5 GeV for antineutrinos; ν<2 GeV and ν<5 GeV for E>9 GeV and E>18 GeV, respectively.

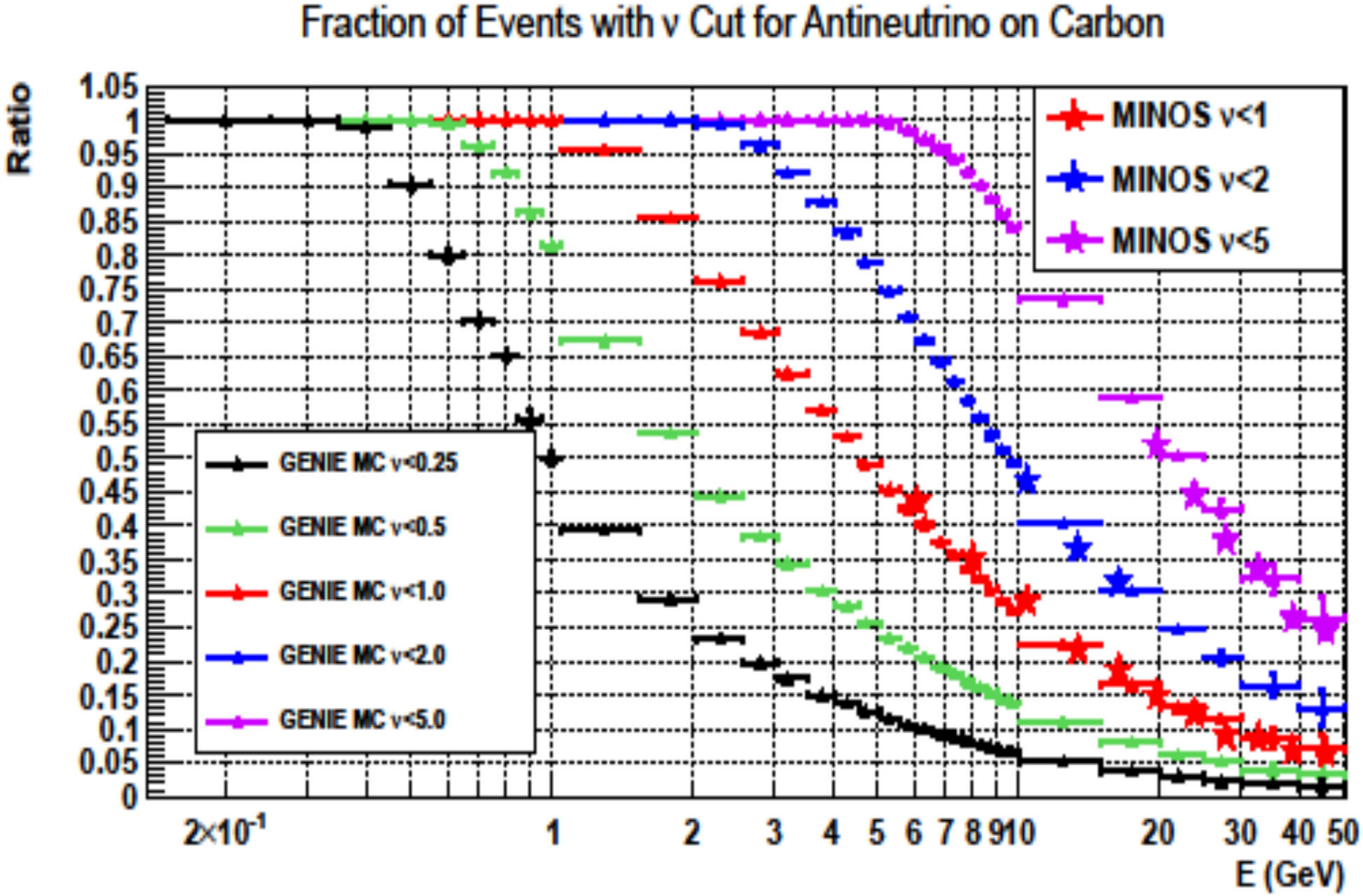




The Low ν Method for Low Energies



The Low ν Method for Low Energies



The Low ν Method for Low Energies

- As the energy decreases, lower ν events should be selected so that their cross section remains below 60%.

The Low ν Method for Low Energies

- We examine the use of

  a) ν<0.25 GeV for E_{ν}>0.7 GeV, $E_{\overline{\nu}}$>1 GeV

  and

  b) ν<0.5 GeV for E_{ν}>1.2 GeV, $E_{\overline{\nu}}$>2 GeV

  on CC events.

…ν_{max}=0.25…

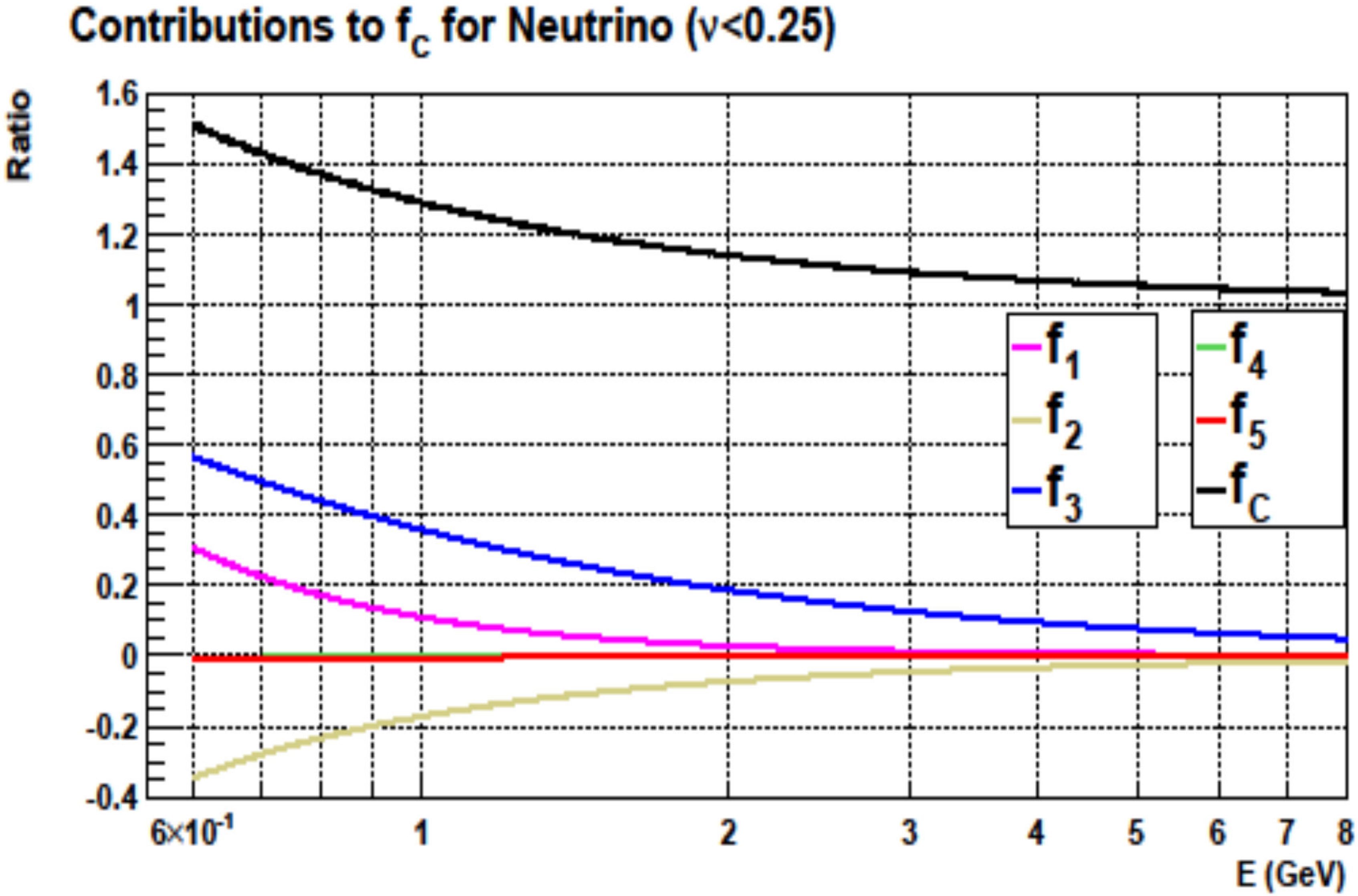
…ν_{max}=0.25: Methodology…

- The cross section for ν_{max}=0.25 is almost entirely QE:

$$\nu n \rightarrow \mu^- p \,/\, \bar{\nu} p \rightarrow \mu^+ n$$

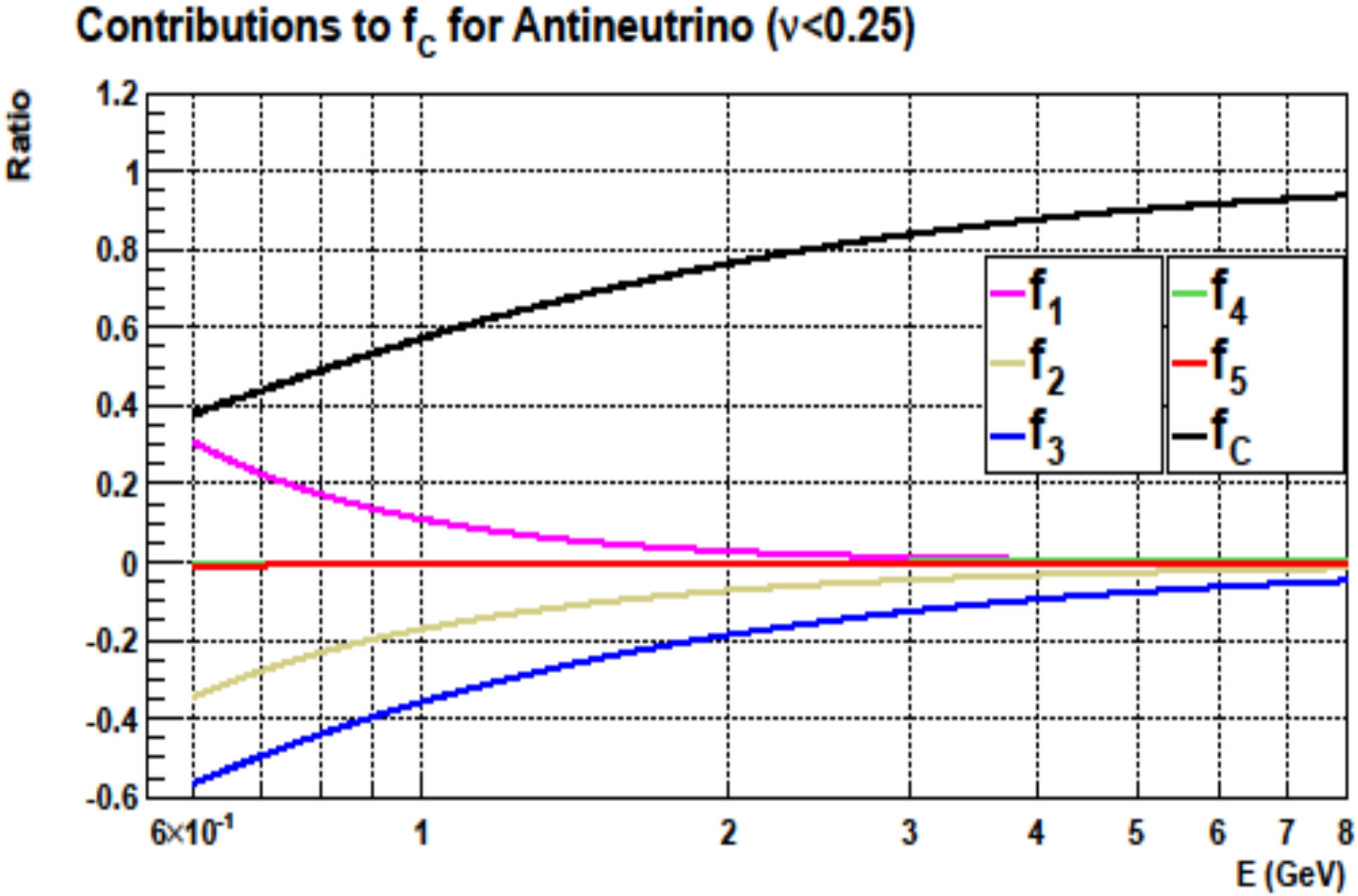
- Structure function ratios are well known for QE on free nucleons, so f_C should have very small systematic uncertainties on hydrogen and deuterium.
- ${}^{12}_{6}C$ targets: Cross section corrections for nuclear effects are necessary: Pauli suppression (Paschos and Yu, 2002) on the differential cross section.
- Recent update from Bodek, Budd and Christy with QE transverse enhancement at low energy for nuclear targets.

…ν_{max}=0.25: f_C…



Contributions to f_C for Neutrino (ν<0.25)
Ratio
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
6×10^-1
1
2
3
4
5
6
7
8
E (GeV)
f_1
f_2
f_3
f_4
f_5
f_C

…ν_{max}=0.25: f_C…



Contributions to f_C for Antineutrino (ν<0.25)
Ratio
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
6×10^-1
1
2
3
4
5
6
7
8
E (GeV)
f_1
f_2
f_3
f_4
f_5
f_C

…ν_{max}=0.25: Conclusion…

- If we apply the MINOS criterion of 60%, the method works for E>0.7 GeV for ν_μ and E>1 GeV for $\bar{\nu}_\mu$ with model uncertainties 3.8% and 5%, respectively.

…ν_{max}=0.5…

…ν_{max}=0.5…

- Primary contributors: QE + Single-pion W<1.4 GeV
- Single-pion major contributor: Delta ($J = \frac{3}{2}, P_{33}(1232)$) resonance

$$\nu p \rightarrow \mu^- \Delta^{++} / \bar{\nu} n \rightarrow \mu^+ \Delta^- :$$

$$\nu p \rightarrow \mu^- p \pi^+ / \bar{\nu} n \rightarrow \mu^+ n \pi^-$$

$$\nu n \rightarrow \mu^- \Delta^+ / \bar{\nu} p \rightarrow \mu^+ \Delta^0 :$$

$$\nu n \rightarrow \mu^- n \pi^+ / \bar{\nu} p \rightarrow \mu^+ p \pi^-$$

$$\nu n \rightarrow \mu^- p \pi^0 / \bar{\nu} p \rightarrow \mu^+ n \pi^0$$

- Some higher resonances and the non-resonant continuum
- Almost negligible coherent (below, A = nucleus):

$$\nu A \rightarrow \mu^- A \pi^+ / \bar{\nu} A \rightarrow \mu^+ A \pi^-$$

…ν_{max}=0.5: Methodology…

- Cross section fits of delta resonance differ for high and low energy experiments.
- For the resonance region calculation, we define the delta interactions for W<1.4 as the single-pion final-state interactions. Therefore, our definition includes the non-resonant continuum even though we will collectively call it delta.
- We use Paschos 2011 equations for delta resonance on free nucleons, apply absolute cross section scaling of 1/1.2 to exclude W>1.4 GeV and vary M_A and ${C_5}^A$ to fit BEBC90 single-pion W<1.4 GeV results.
- For carbon, we again apply Pauli suppression.

…ν_{max}=0.5: Plots with GENIE MC…

- The total $\nu < 0.5$ GeV cross section flattens as E increases: Reasonably flat for 10-20 GeV
- In order to compare our predictions to GENIE and make the method accessible for future experimental application, we normalize to 10-20 GeV (average 15.1 GeV for GENIE) and define:

$$\bar{f}_{C:\nu<\nu_{max}}(15.1)(E) \coloneqq \frac{f_{C:\nu<\nu_{max}}(E)}{f_{C:\nu<\nu_{max}}(15.1\ GeV)}$$

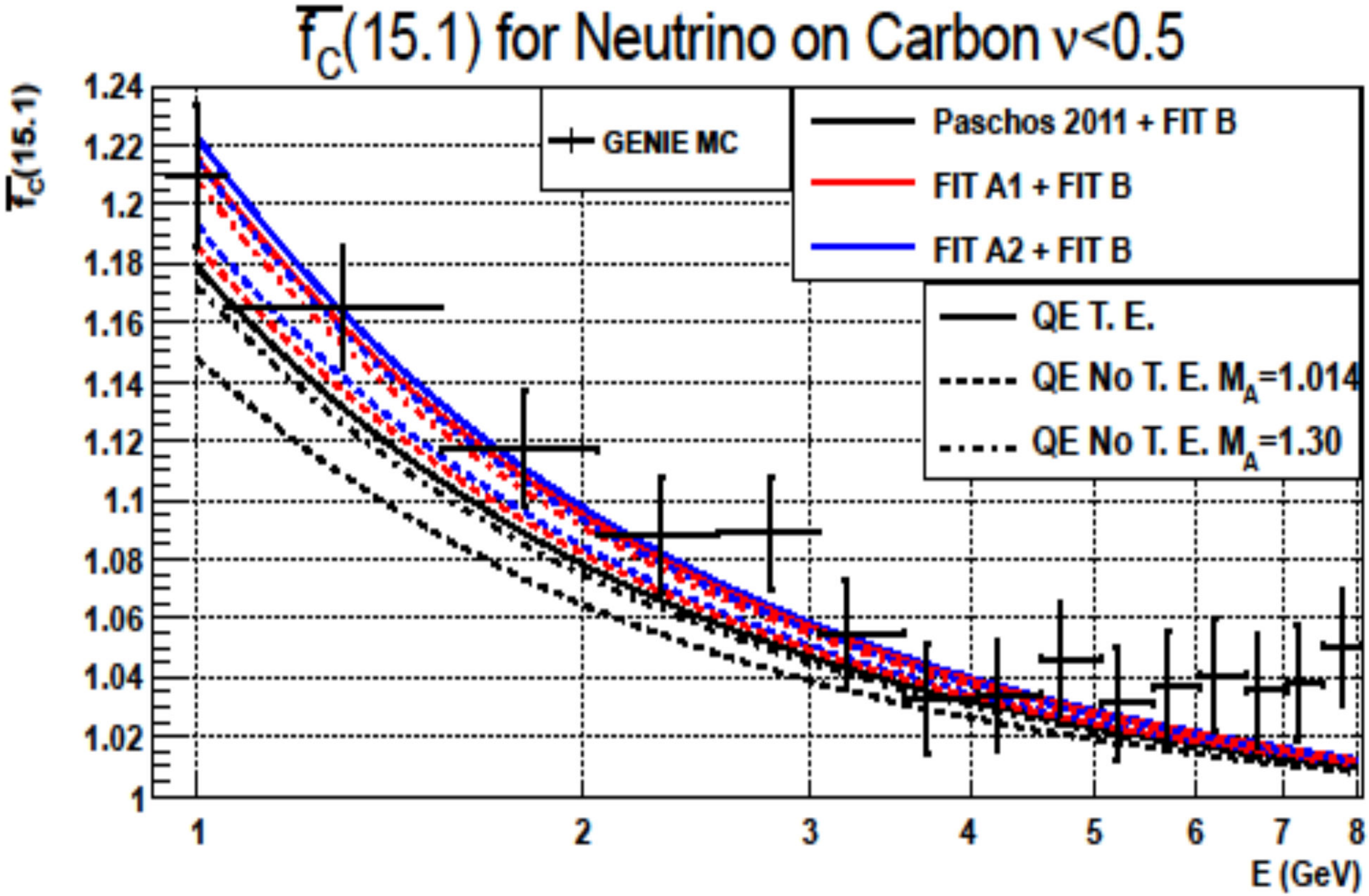
…ν_{max}=0.5…

- Curve legend for the following plots (carbon targets, applying Pauli blocking to differential cross section):

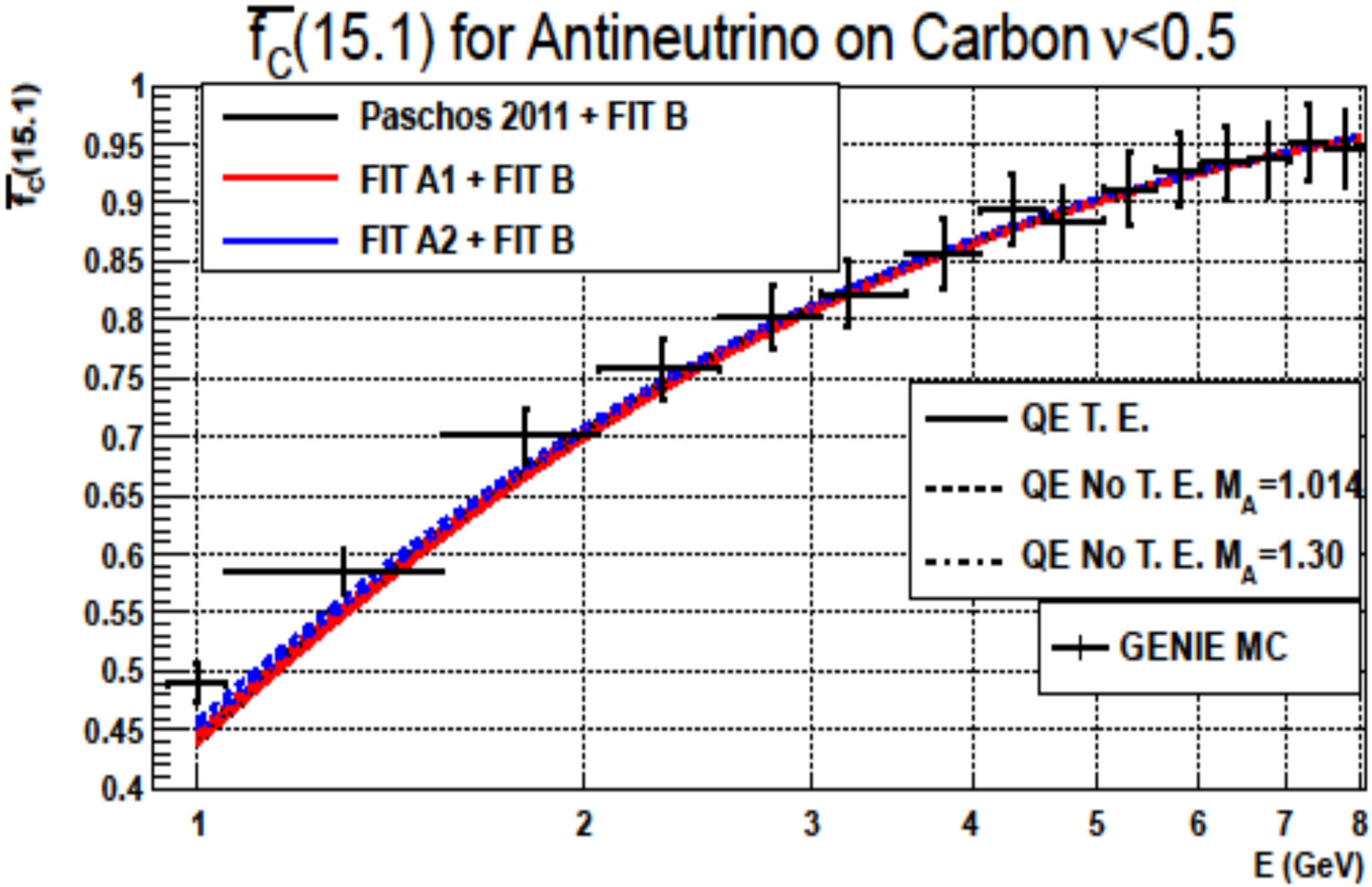
  $\nu p \rightarrow \mu^{-}\Delta^{++}/\ \bar{\nu}n \rightarrow \mu^{+}\Delta^{-}$
  Paschos 2011: $M_A = 1.05$; ${C_5}^A = 1.2$ (Original values used by Paschos and Lalakulich, fitting ANL and BNL low energy data)
  FIT-A1: $M_A = 1.93$; ${C_5}^A = 0.62$ (BEBC90 $\bar{\nu}n \rightarrow \mu^{+}\Delta^{-}$ differential and total cross section fit)
  FIT-A2: $M_A = 1.75$; ${C_5}^A = 0.49$ (BEBC90 $\nu p \rightarrow \mu^{-}\Delta^{++}$ differential and total cross section fit)

  $\nu n \rightarrow \mu^{-}\Delta^{+}/\ \bar{\nu}p \rightarrow \mu^{+}\Delta^{0}$
  FIT-B: $M_A = 1.62$; ${C_5}^A = 1.27$ (BEBC90 $\nu n \rightarrow \mu^{-}\Delta^{+}$ differential and total cross section fit)

…ν_{max}=0.5: $\bar{f}_C$…



…ν_{max}=0.5: $\bar{f}_C$…



…ν_{max}=0.5: Conclusion

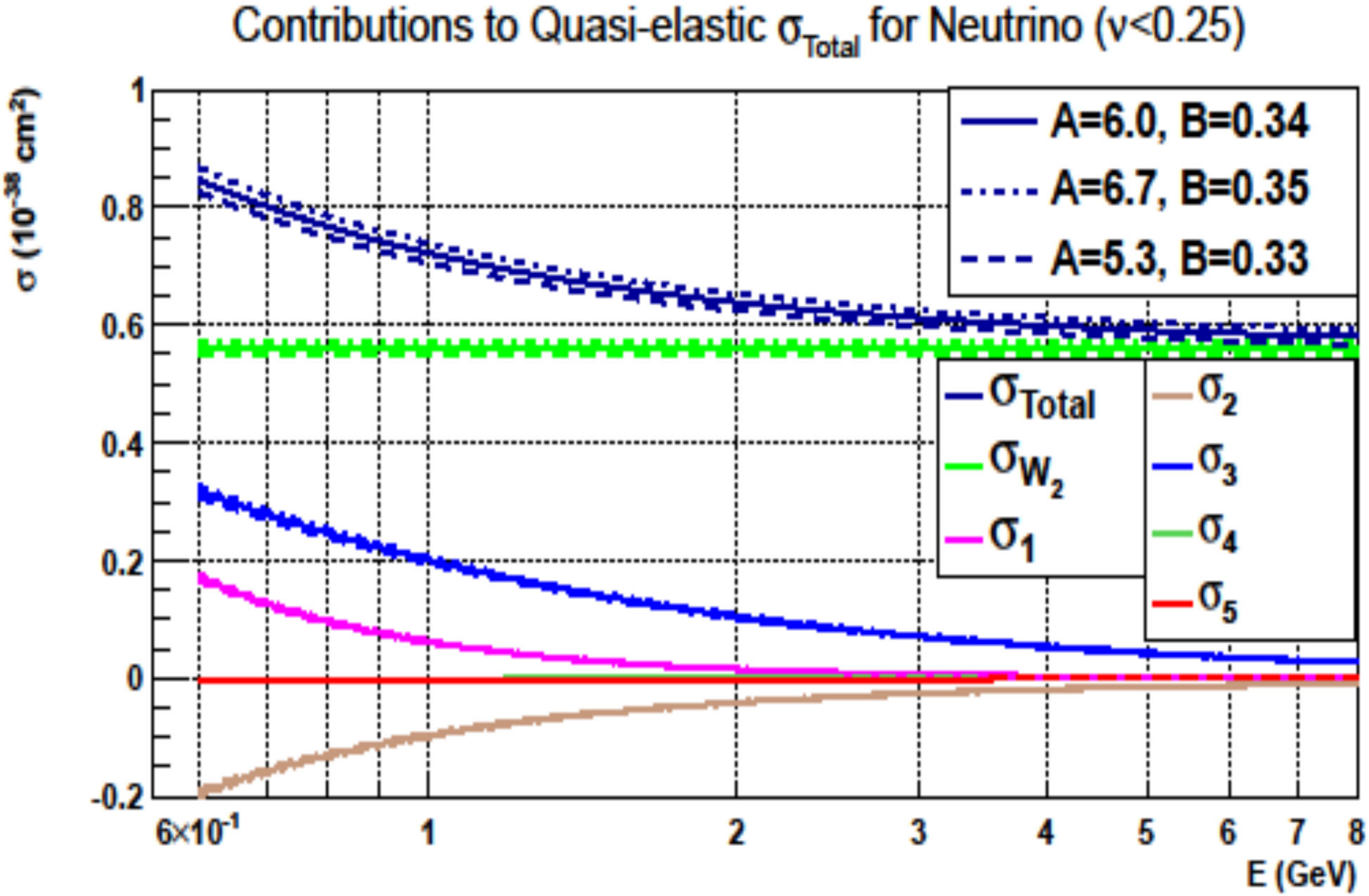
- Depending on the model used, Δf_C is within 2.6% for ν_μ above 1.2 GeV and 1.4% for $\bar{\nu}_\mu$ above 2 GeV.
- Above these energies, the ratios to total cross section are below 60%.

Back-up Slides

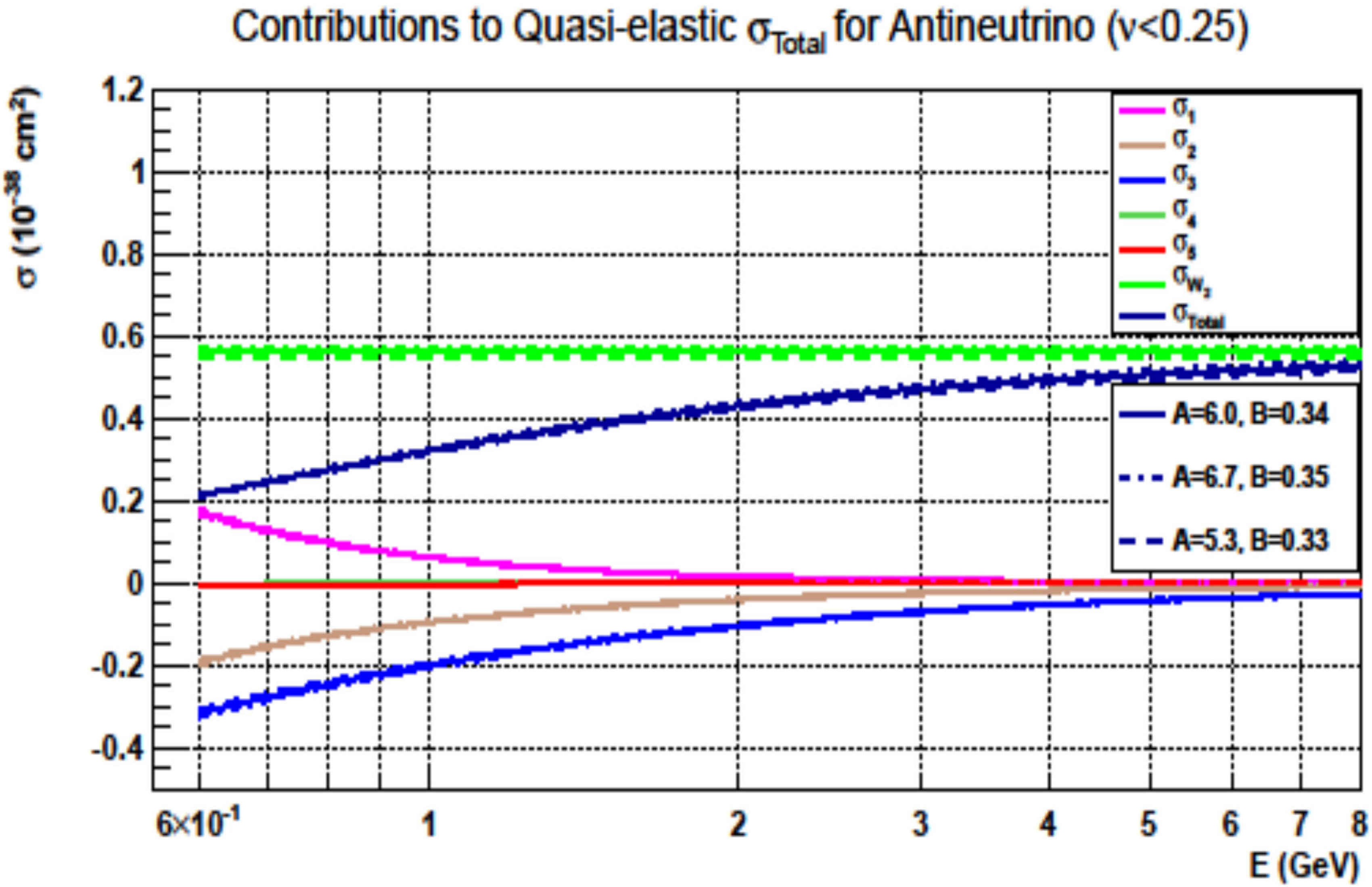
Other Methods Available for MINERvA

- Modeling the production of pions and kaons produced from the proton beam, tracking them along the horn magnetic focus and modeling their decay:
  -> Differential cross section over a thick target and a reliable model for the magnetic field
- Measuring the muon flux that exits the decay pipe:
  -> Response of detectors at the end of the decay pipe
  -> Muon energy not measured
- Monitoring inverse muon decay:
  -> Above around 12 GeV, no antineutrinos, useful to constrain flux at high energies
- Monitoring muon neutrino-electron scattering:
  -> Useful only for total flux since calorimetric detectors cannot distinguish the leptons' charge

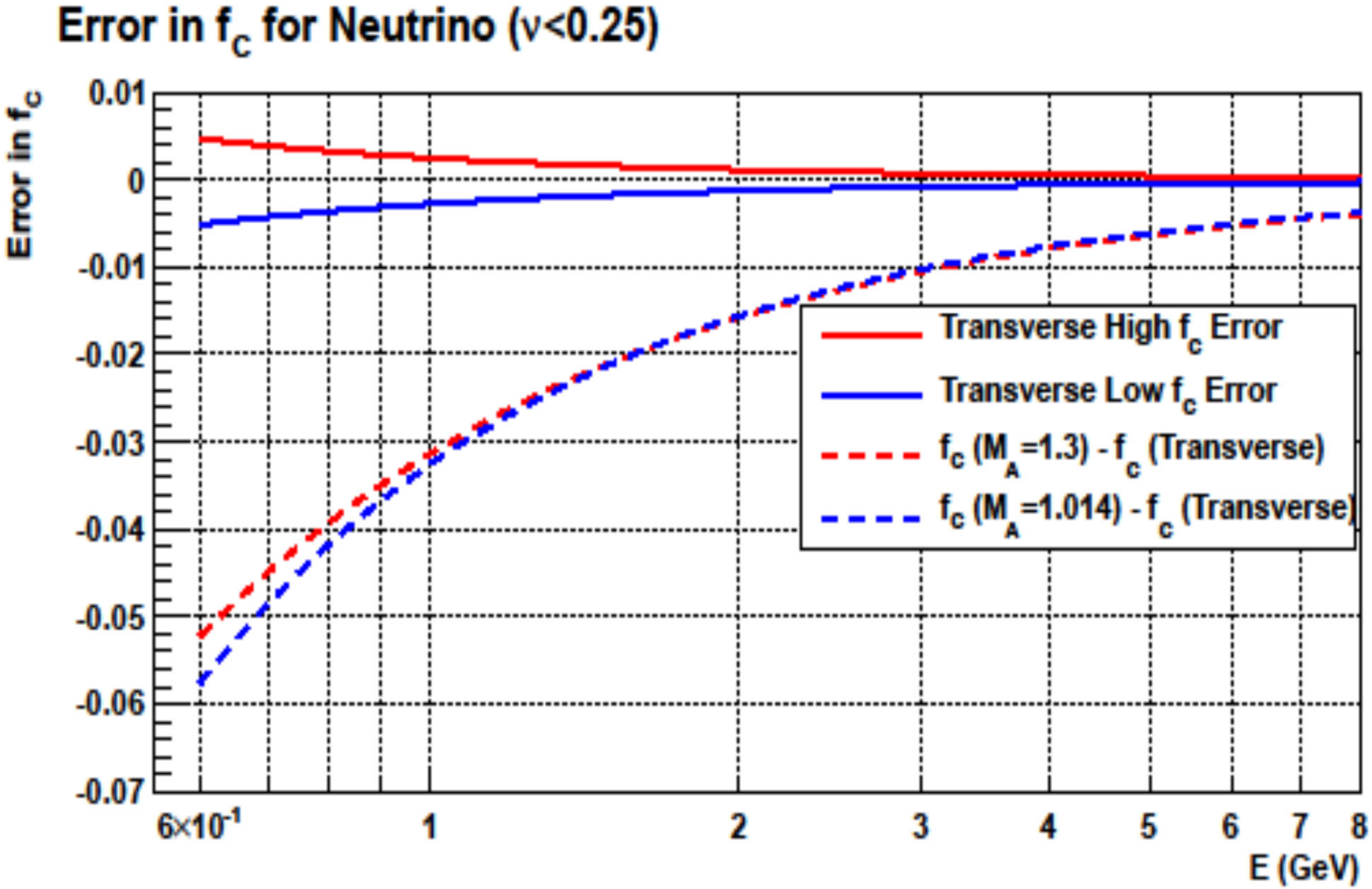
…ν_{max}=0.25: Cross sections…



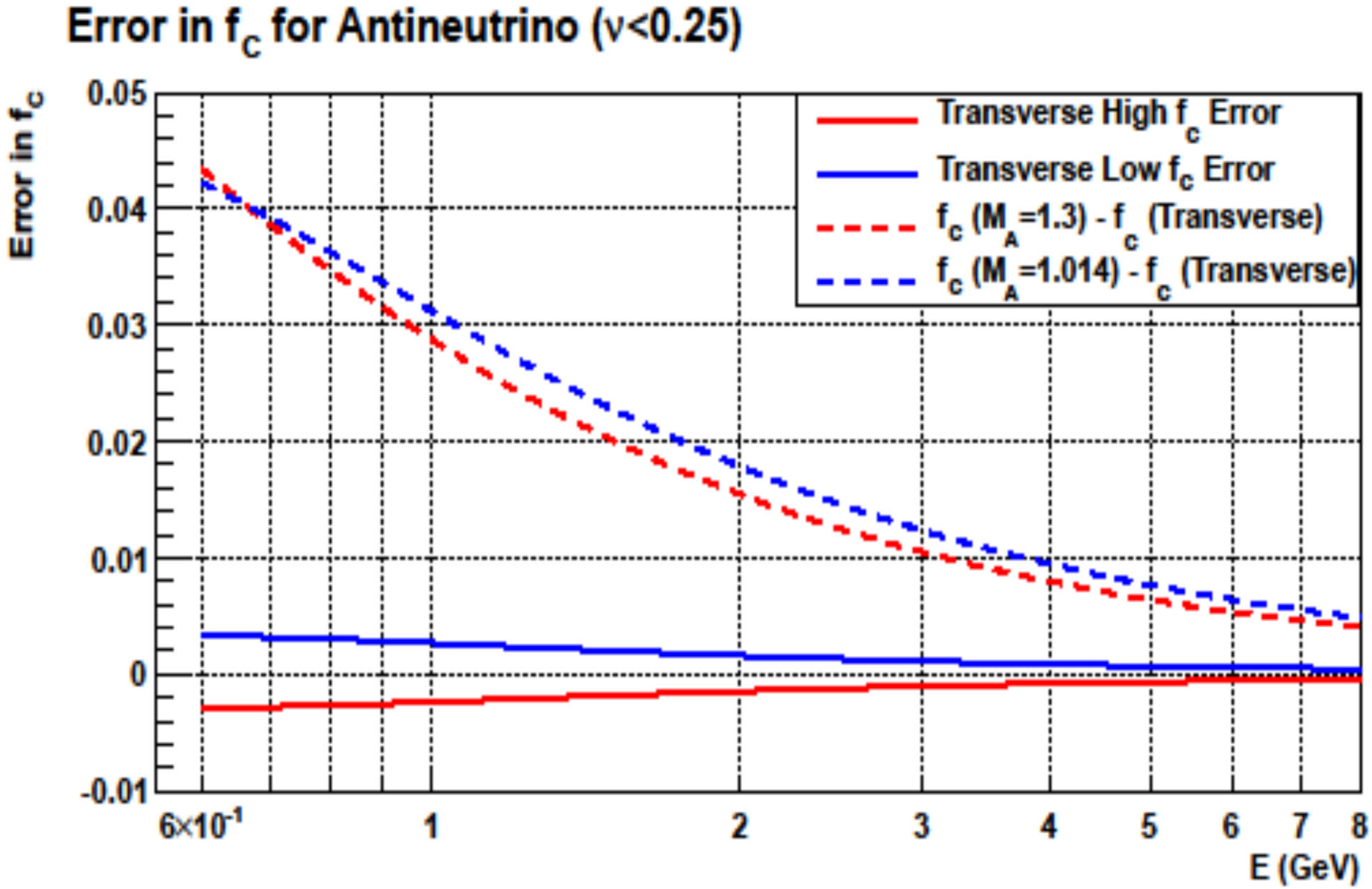
…ν_{max}=0.25: Cross sections…



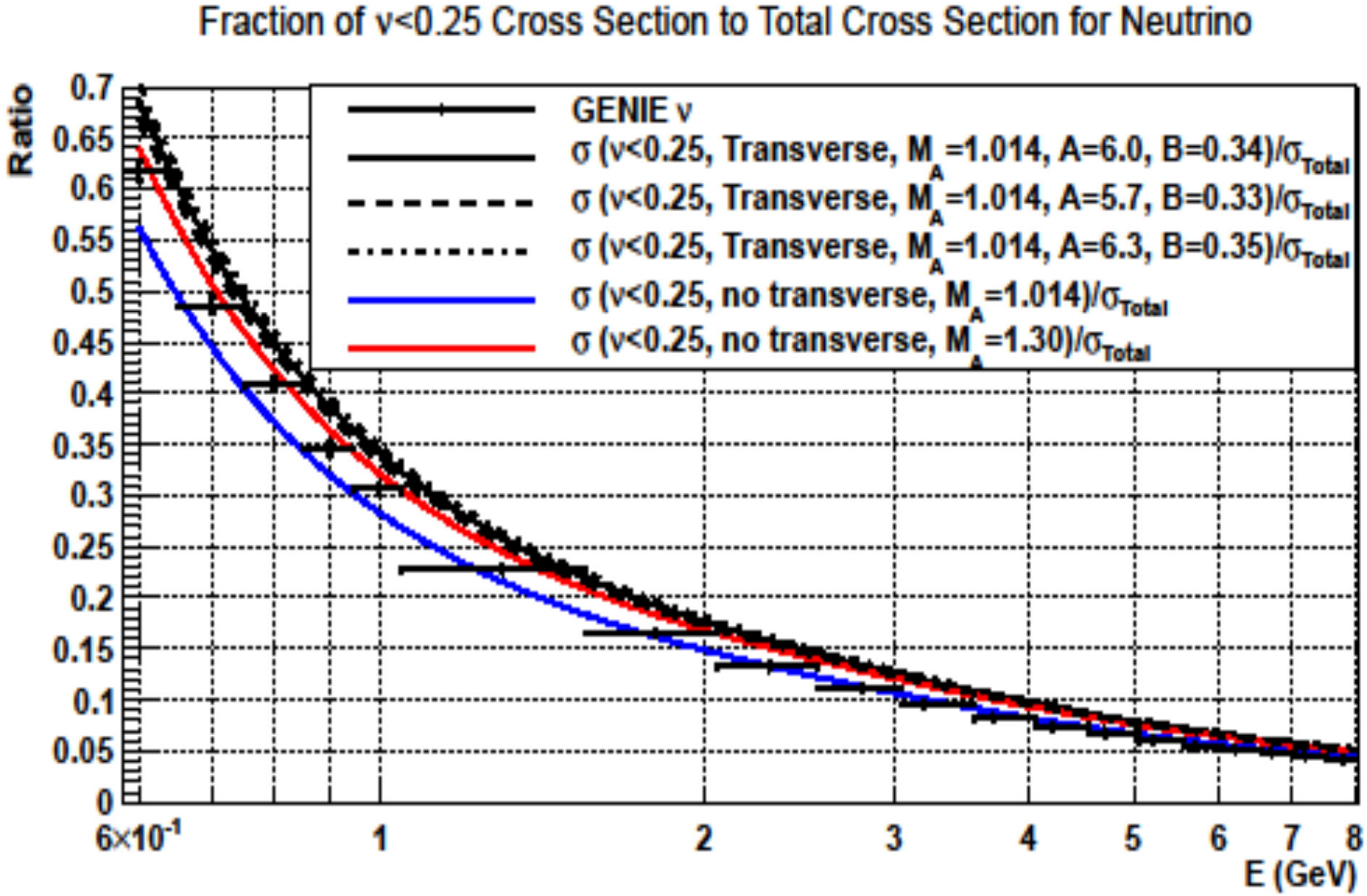
…ν_{max}=0.25: f_C Error…



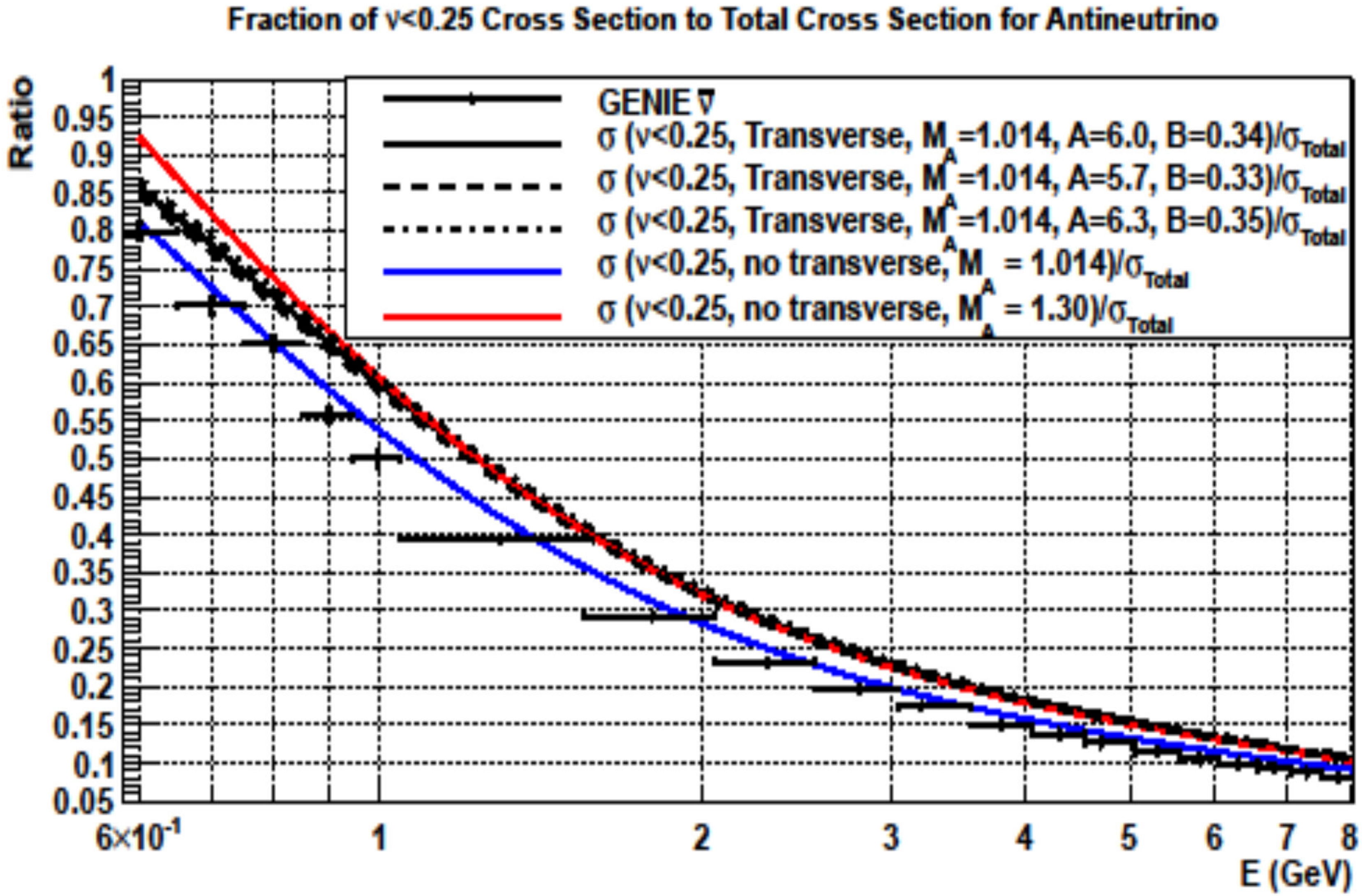
…ν_{max}=0.25: f_C Error…



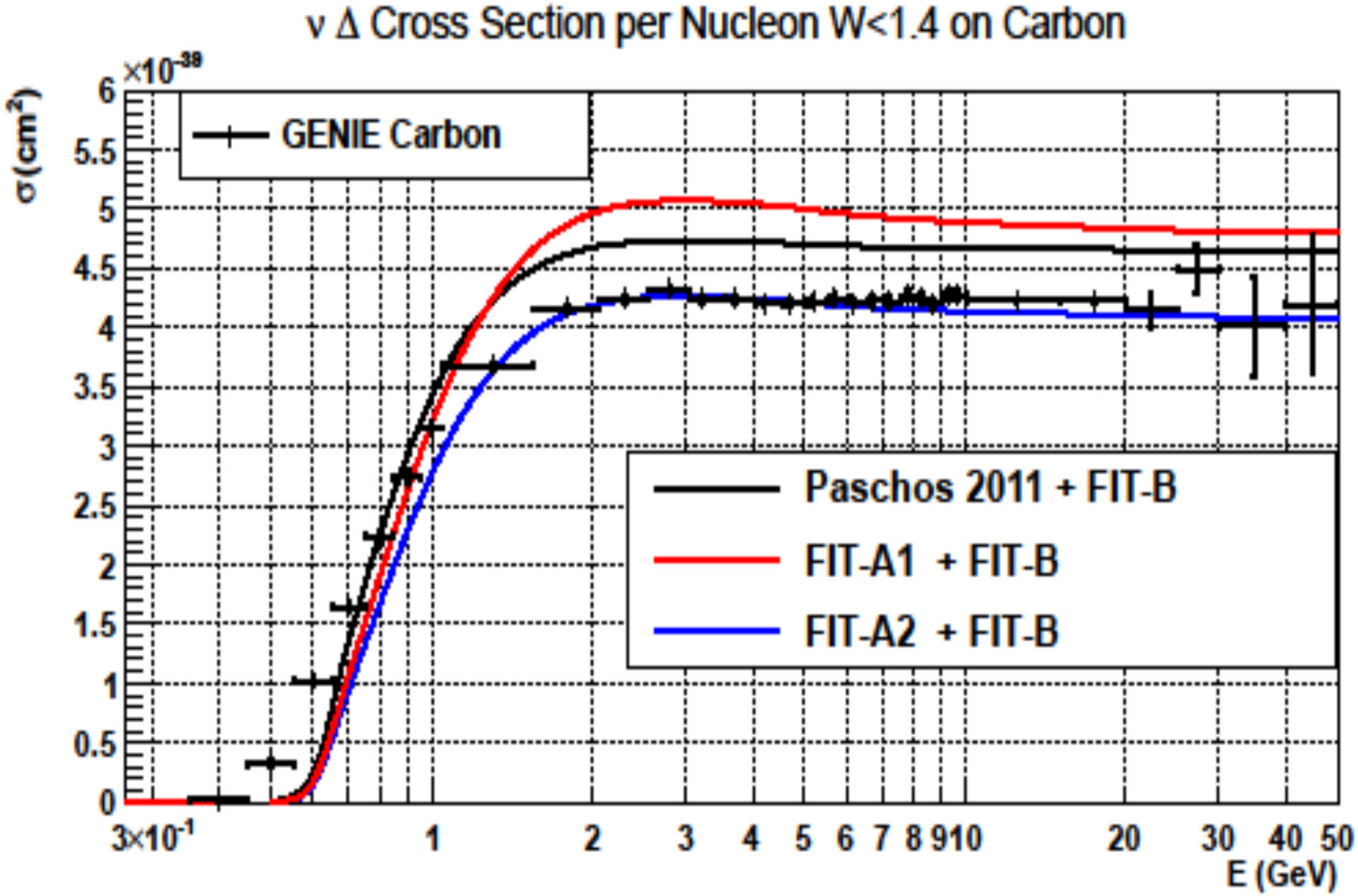
…ν_{max}=0.25: Ratio to Total Parameterization…



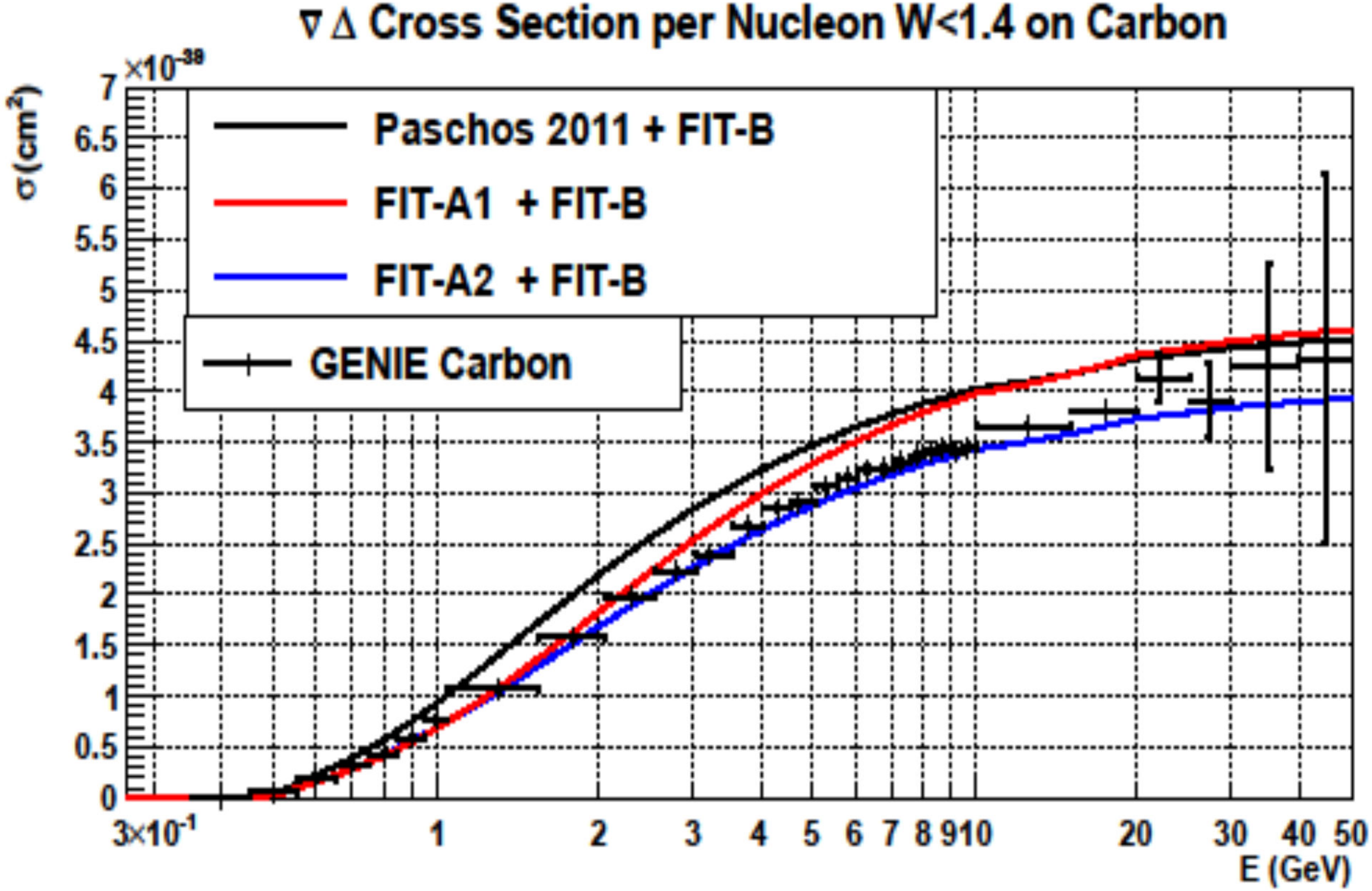
…ν_{max}=0.25: Ratio to Total Parameterization…



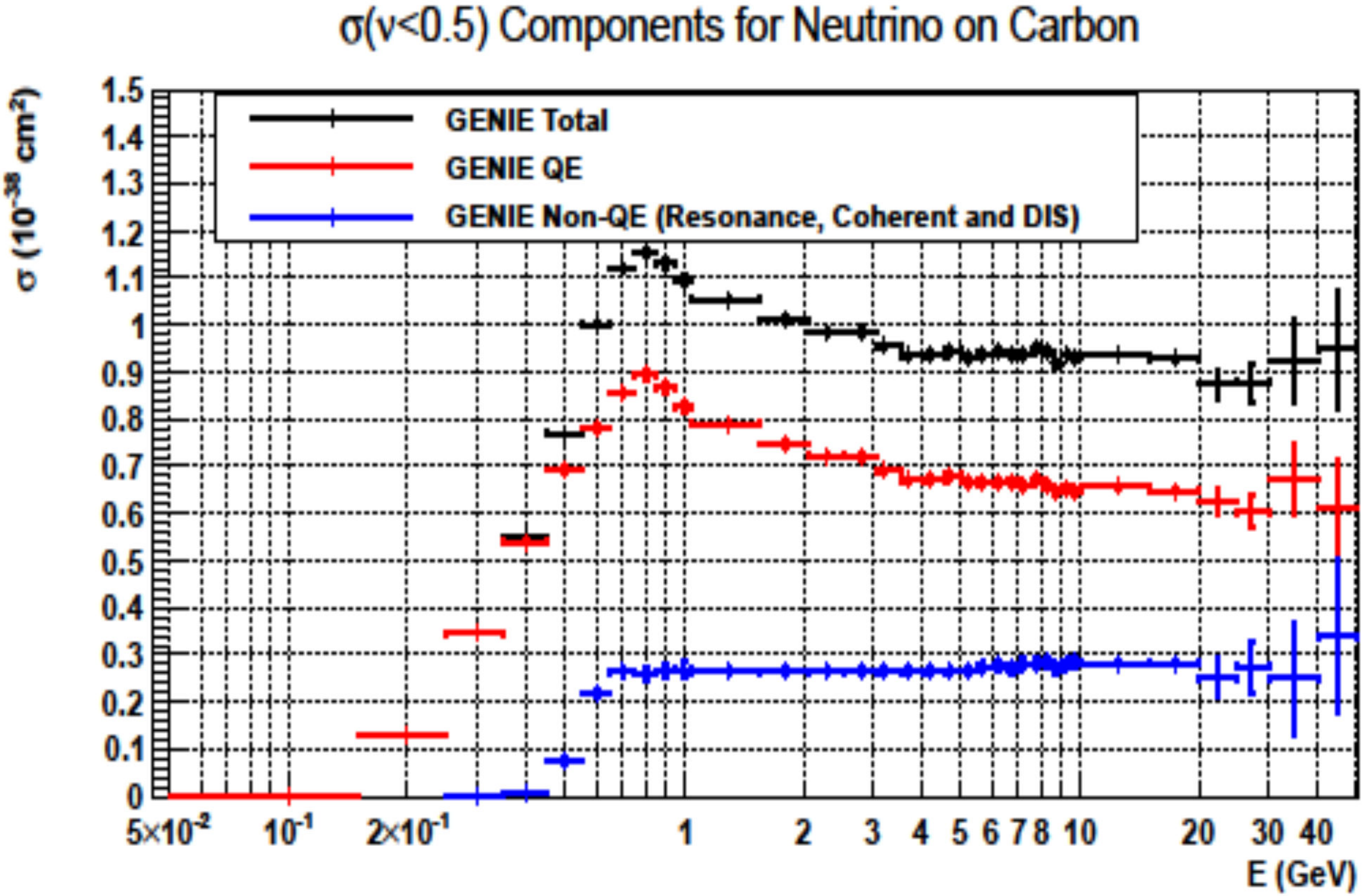
…ν_{max}=0.5: Cross sections…



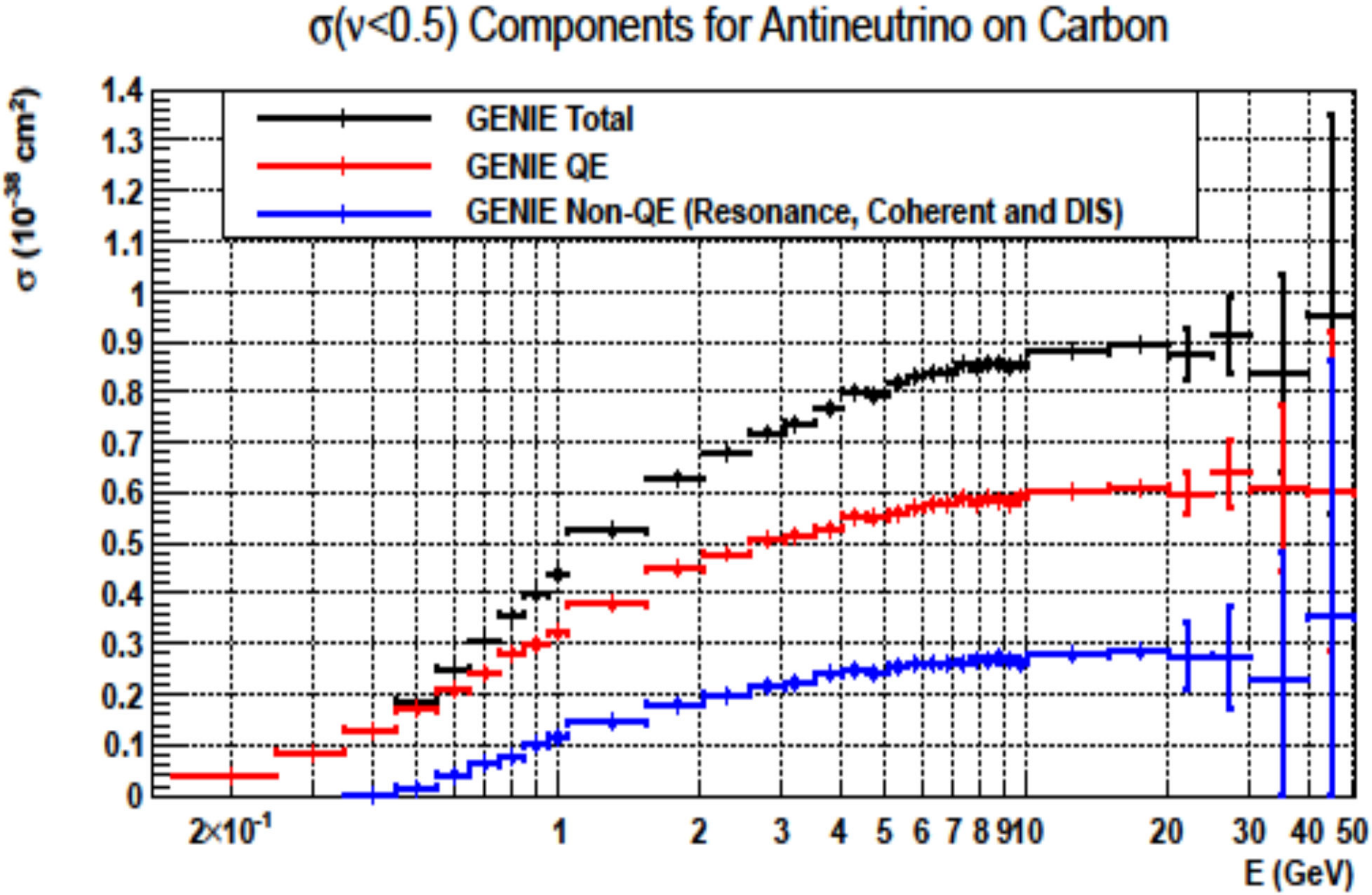
…ν_{max}=0.5: Cross sections…



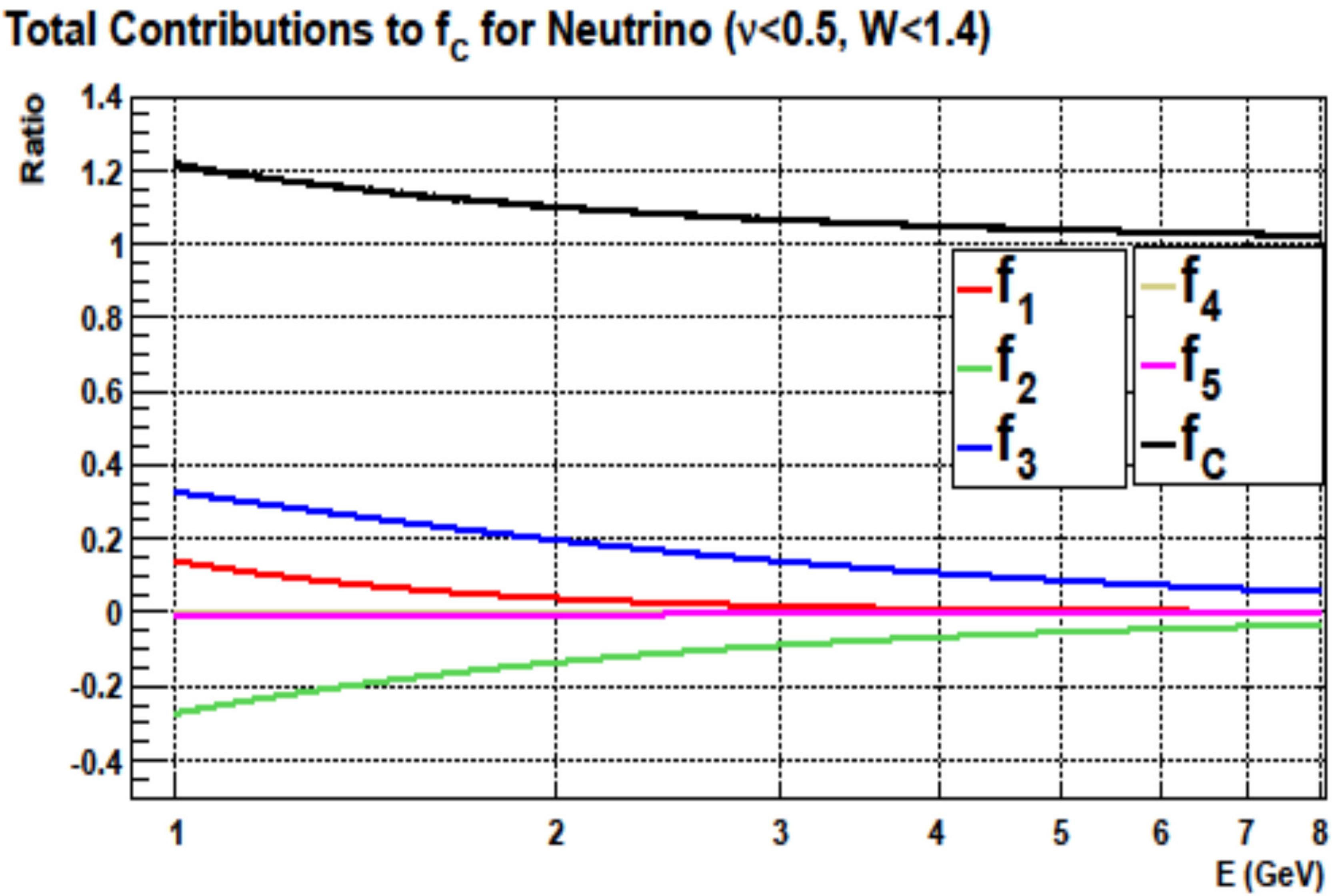
…ν_{max}=0.5: Cross sections…



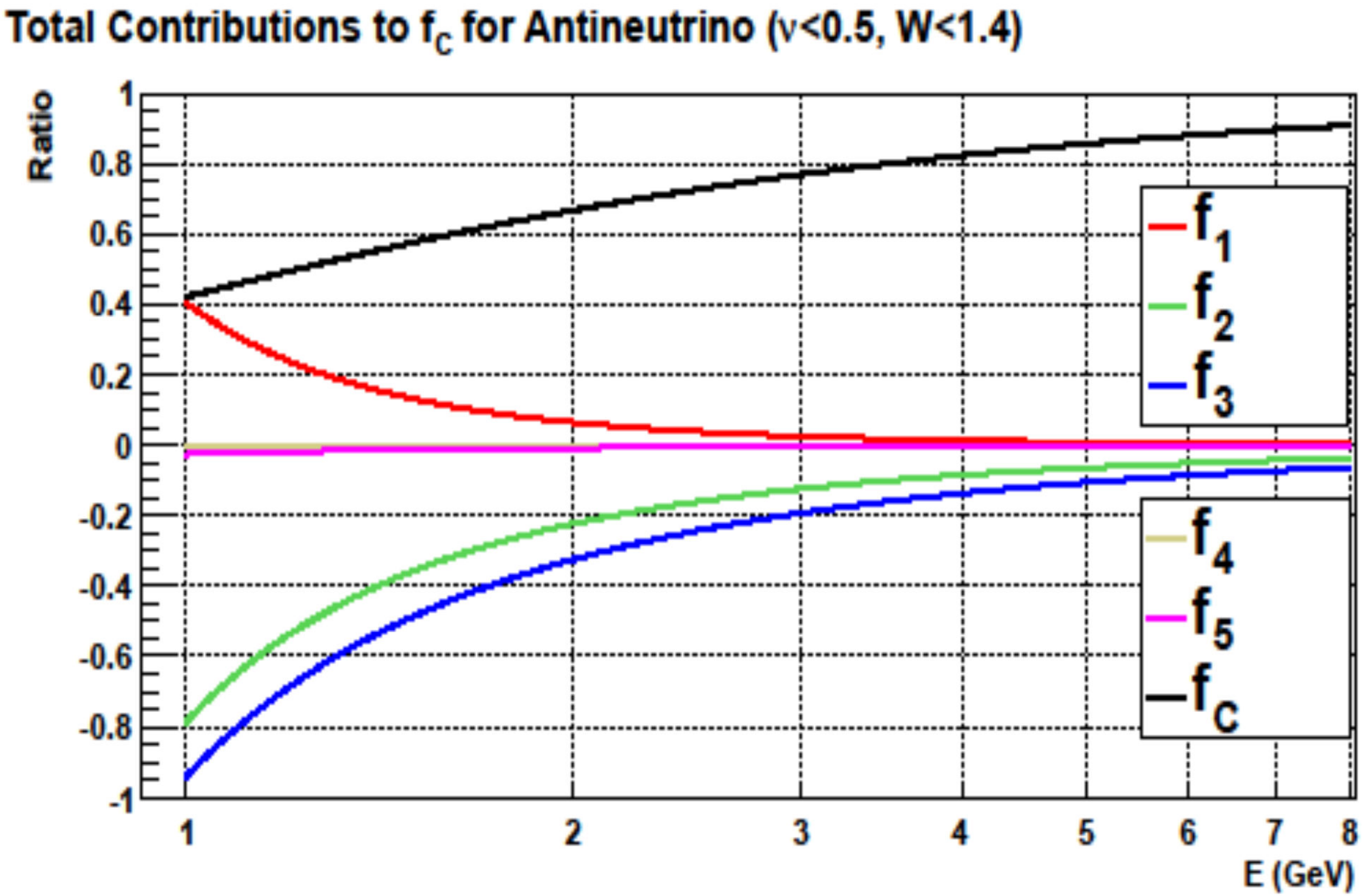
…ν_{max}=0.5: Cross sections…



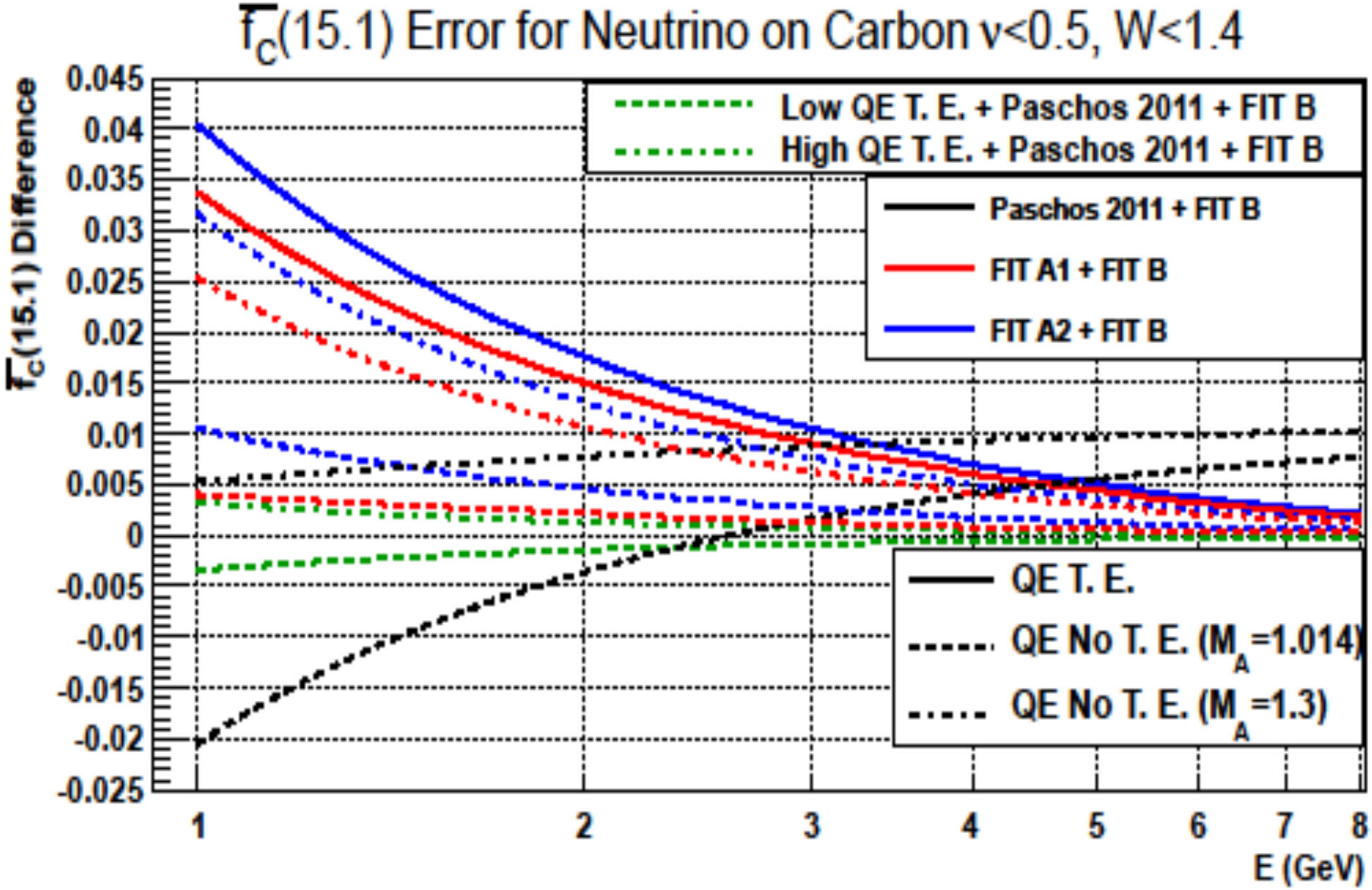
…ν_{max}=0.5: Total = QE T.E. + Paschos 2011 + FIT-B…



…ν_{max}=0.5: Total = QE T.E. + Paschos 2011 + FIT-B…

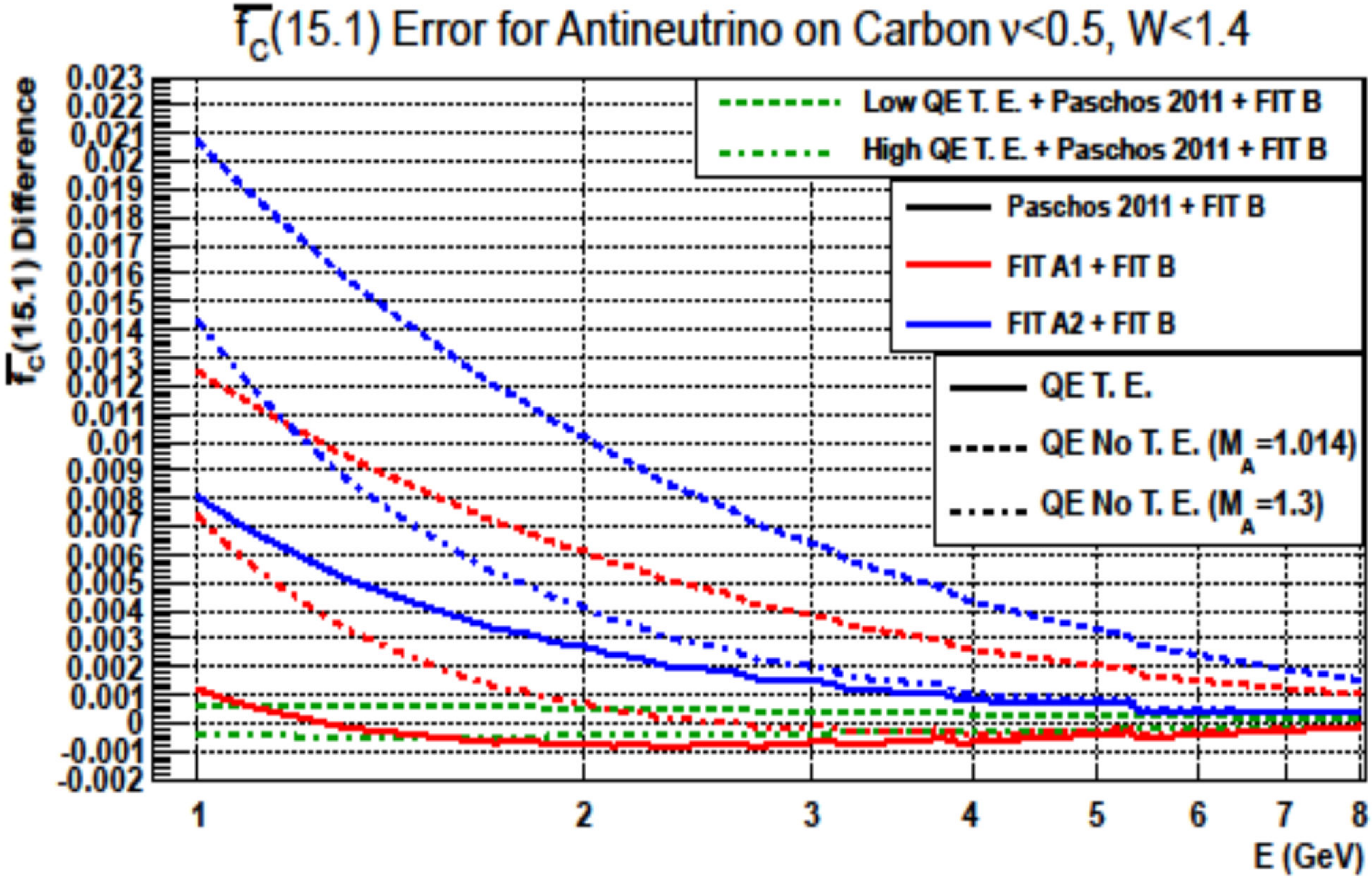


…ν_{max}=0.5…

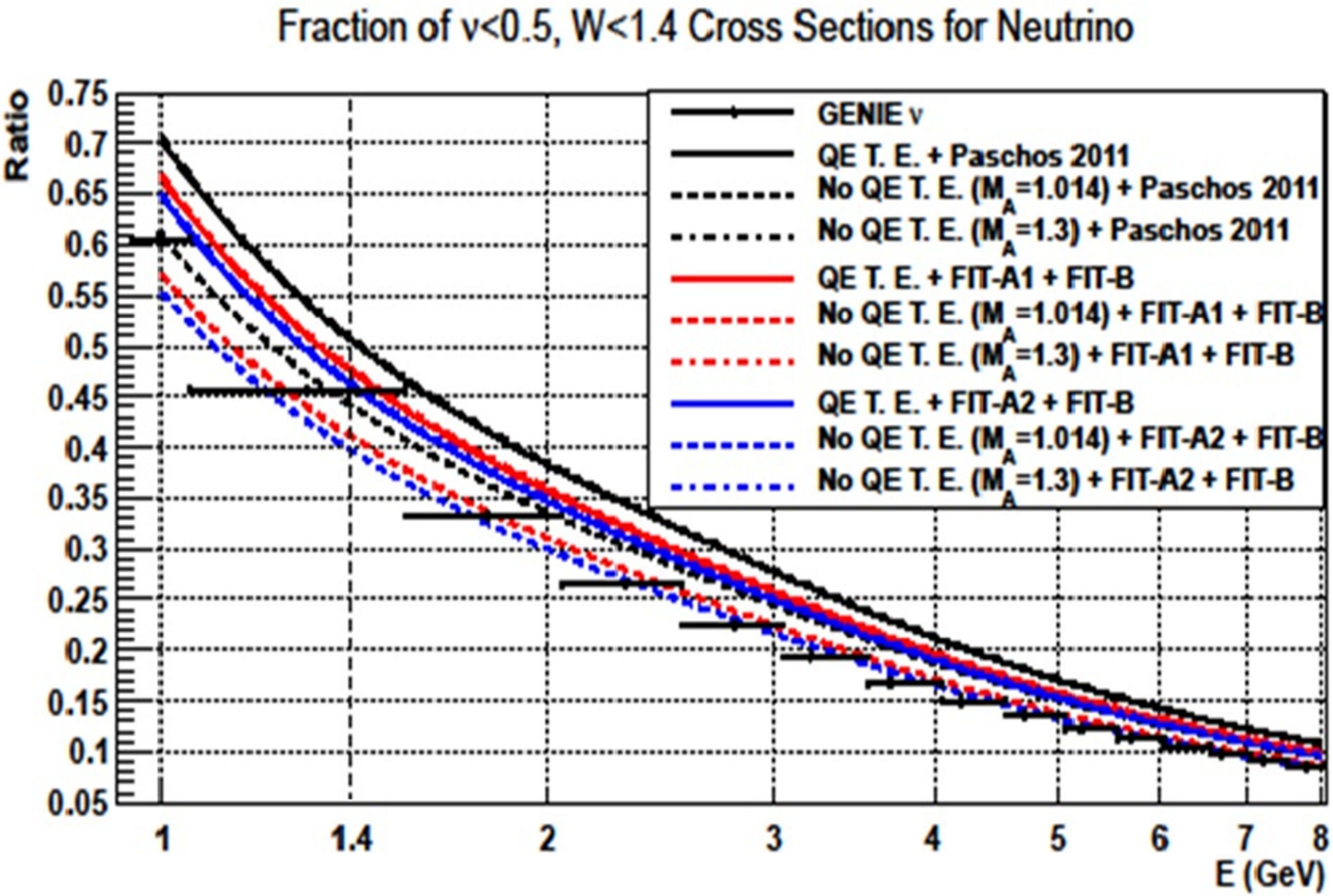


f̄c(15.1) Error for Neutrino on Carbon ν<0.5, W<1.4
f̄c(15.1) Difference
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
Low QE T. E. + Paschos 2011 + FIT B
High QE T. E. + Paschos 2011 + FIT B
Paschos 2011 + FIT B
FIT A1 + FIT B
FIT A2 + FIT B
QE T. E.
QE No T. E. (MA=1.014)
QE No T. E. (MA=1.3)
1
2
3
4
5
6
7
8
E (GeV)

…ν_{max}=0.5…

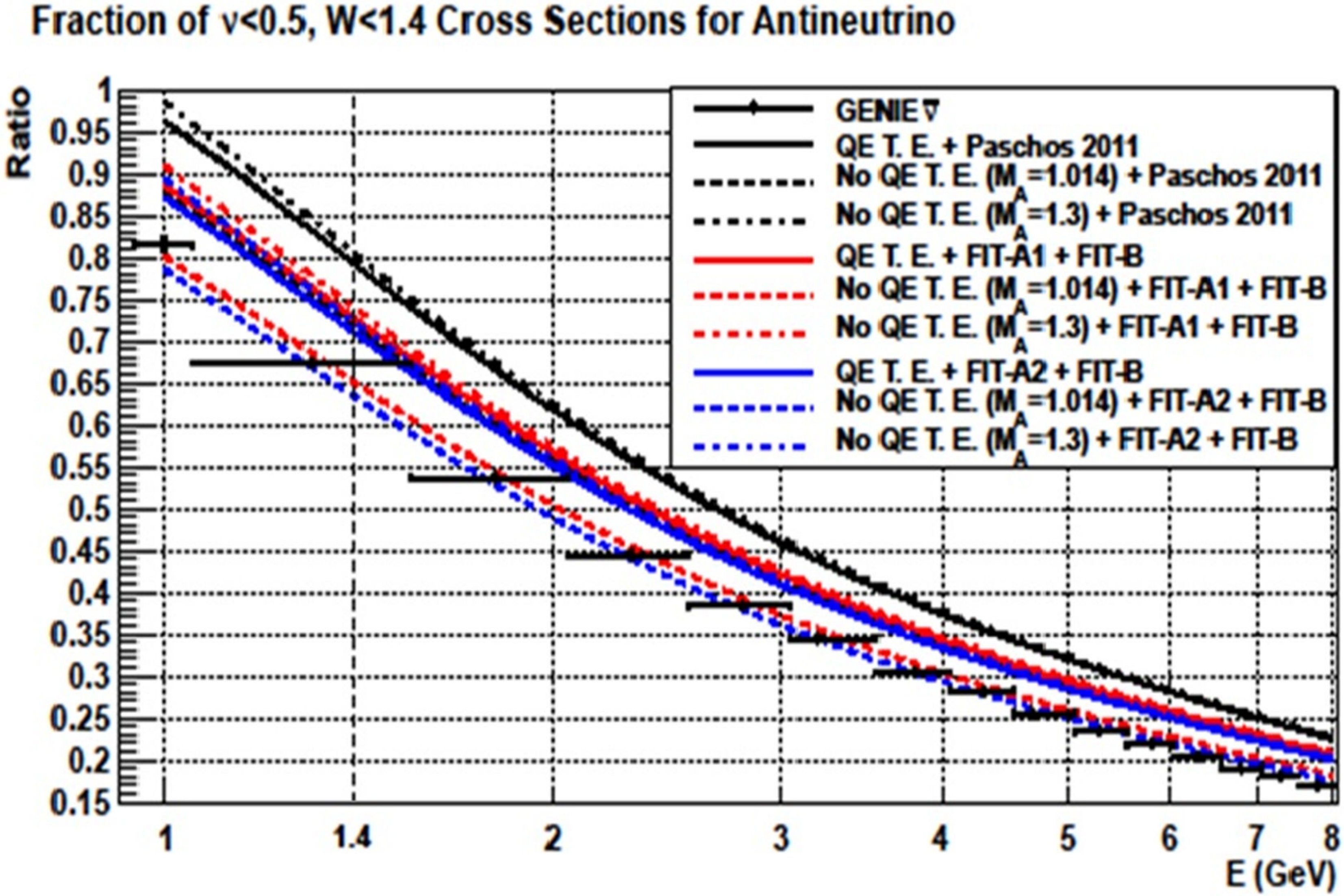

$\overline{f_c}$(15.1) Error for Antineutrino on Carbon ν<0.5, W<1.4
$\overline{f_c}$(15.1) Difference
E (GeV)
Low QE T. E. + Paschos 2011 + FIT B
High QE T. E. + Paschos 2011 + FIT B
Paschos 2011 + FIT B
FIT A1 + FIT B
FIT A2 + FIT B
QE T. E.
QE No T. E. (M_A=1.014)
QE No T. E. (M_A=1.3)

…ν_{max}=0.5…



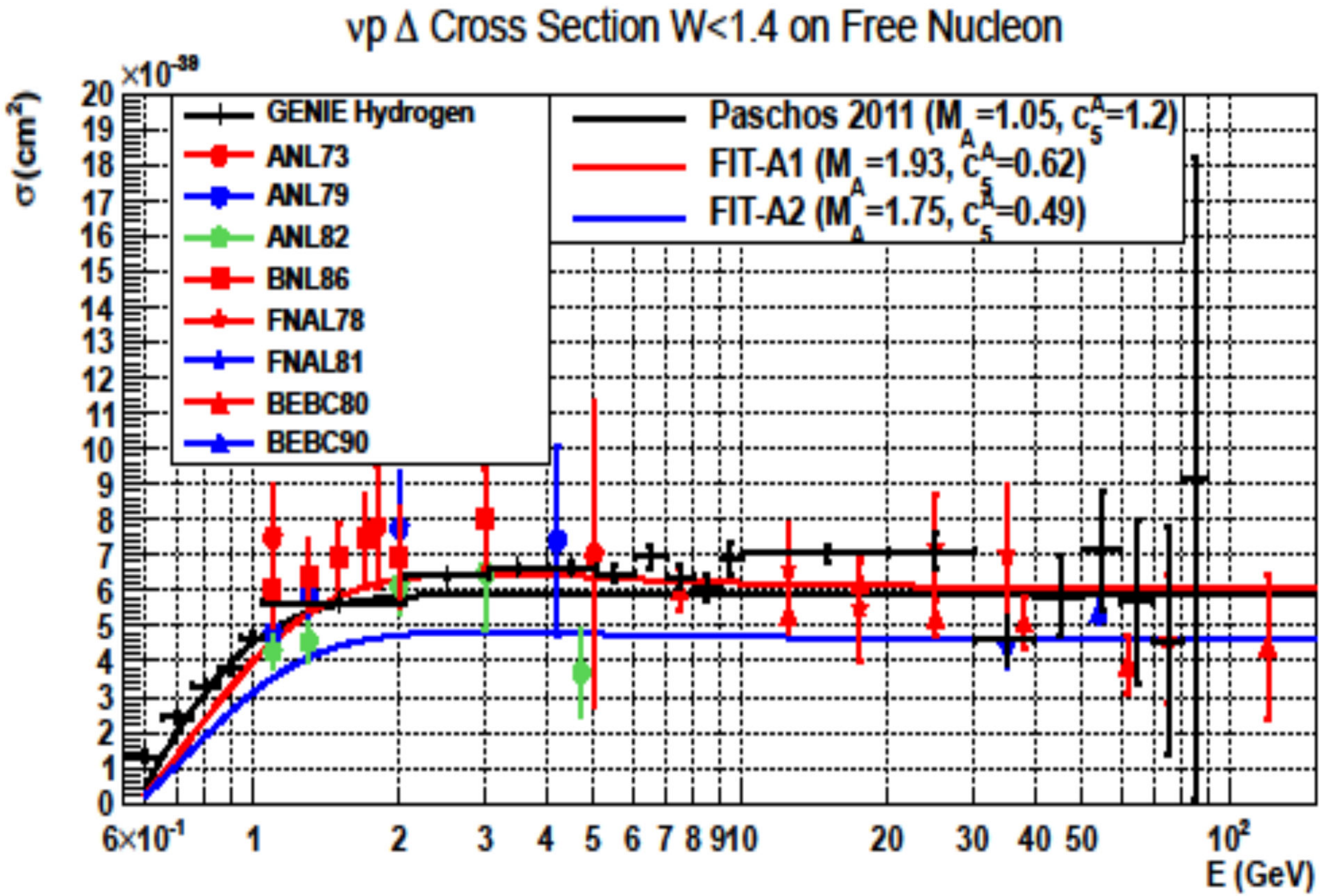
Fraction of ν<0.5, W<1.4 Cross Sections for Neutrino
Ratio
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
1
1.4
2
3
4
5
6
7
8
E (GeV)
GENIE ν
QE T. E. + Paschos 2011
No QE T. E. (M_A=1.014) + Paschos 2011
No QE T. E. (M_A=1.3) + Paschos 2011
QE T. E. + FIT-A1 + FIT-B
No QE T. E. (M_A=1.014) + FIT-A1 + FIT-B
No QE T. E. (M_A=1.3) + FIT-A1 + FIT-B
QE T. E. + FIT-A2 + FIT-B
No QE T. E. (M_A=1.014) + FIT-A2 + FIT-B
No QE T. E. (M_A=1.3) + FIT-A2 + FIT-B

…ν_{max}=0.5…

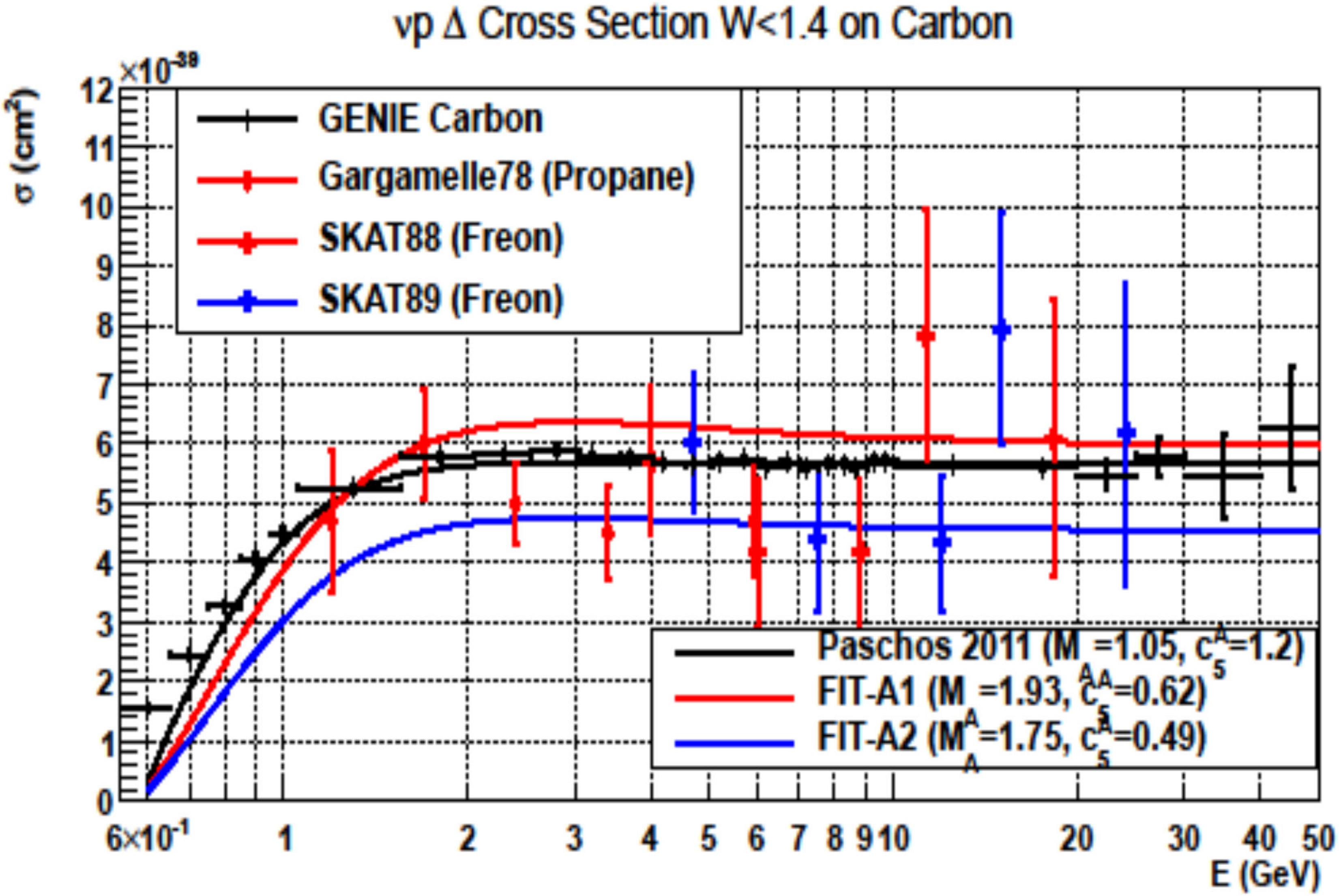


Fraction of ν<0.5, W<1.4 Cross Sections for Antineutrino
Ratio
E (GeV)
GENIE ν̄
QE T. E. + Paschos 2011
No QE T. E. (M_A=1.014) + Paschos 2011
No QE T. E. (M_A=1.3) + Paschos 2011
QE T. E. + FIT-A1 + FIT-B
No QE T. E. (M_A=1.014) + FIT-A1 + FIT-B
No QE T. E. (M_A=1.3) + FIT-A1 + FIT-B
QE T. E. + FIT-A2 + FIT-B
No QE T. E. (M_A=1.014) + FIT-A2 + FIT-B
No QE T. E. (M_A=1.3) + FIT-A2 + FIT-B

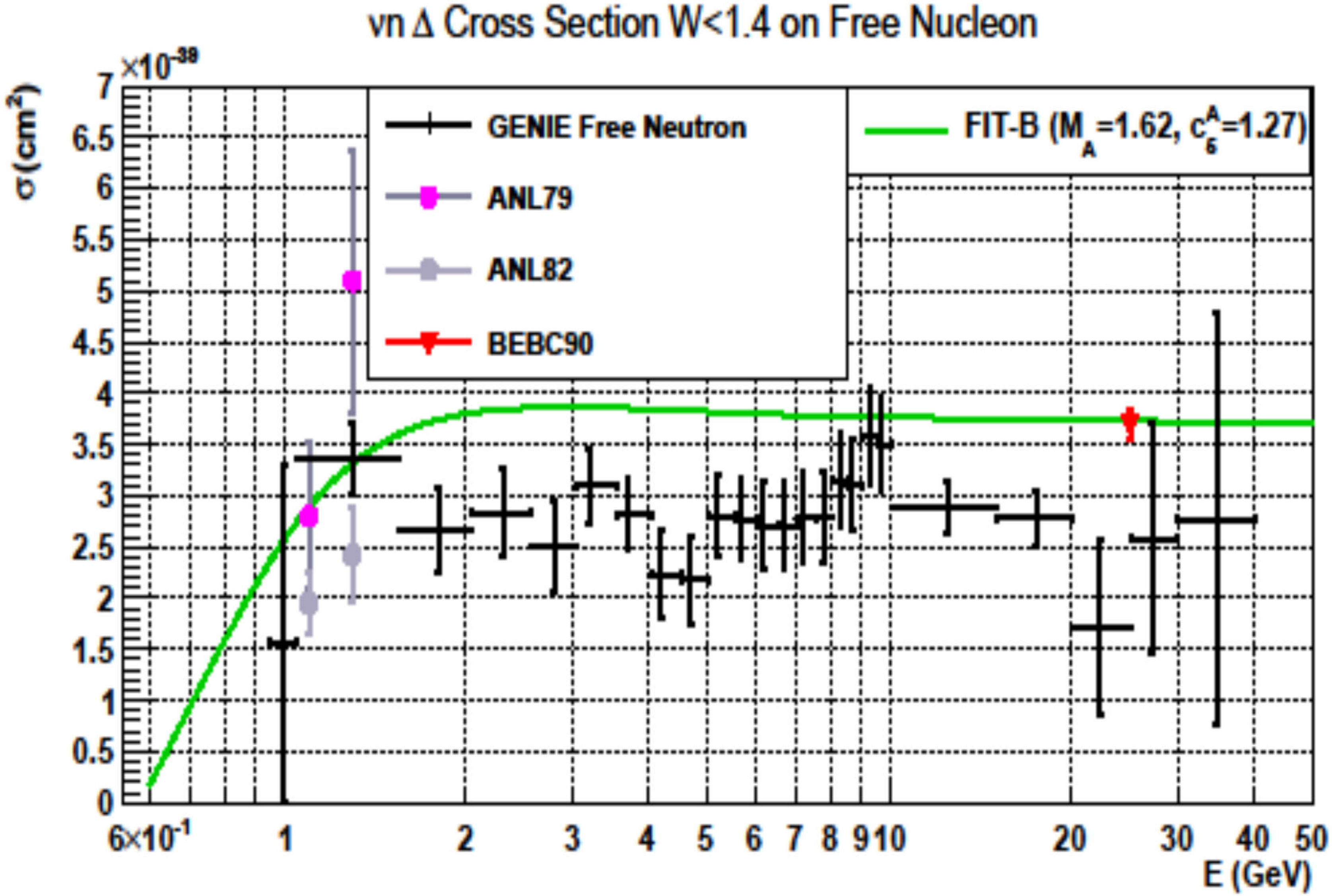
νp Delta Cross Section on Free Nucleon



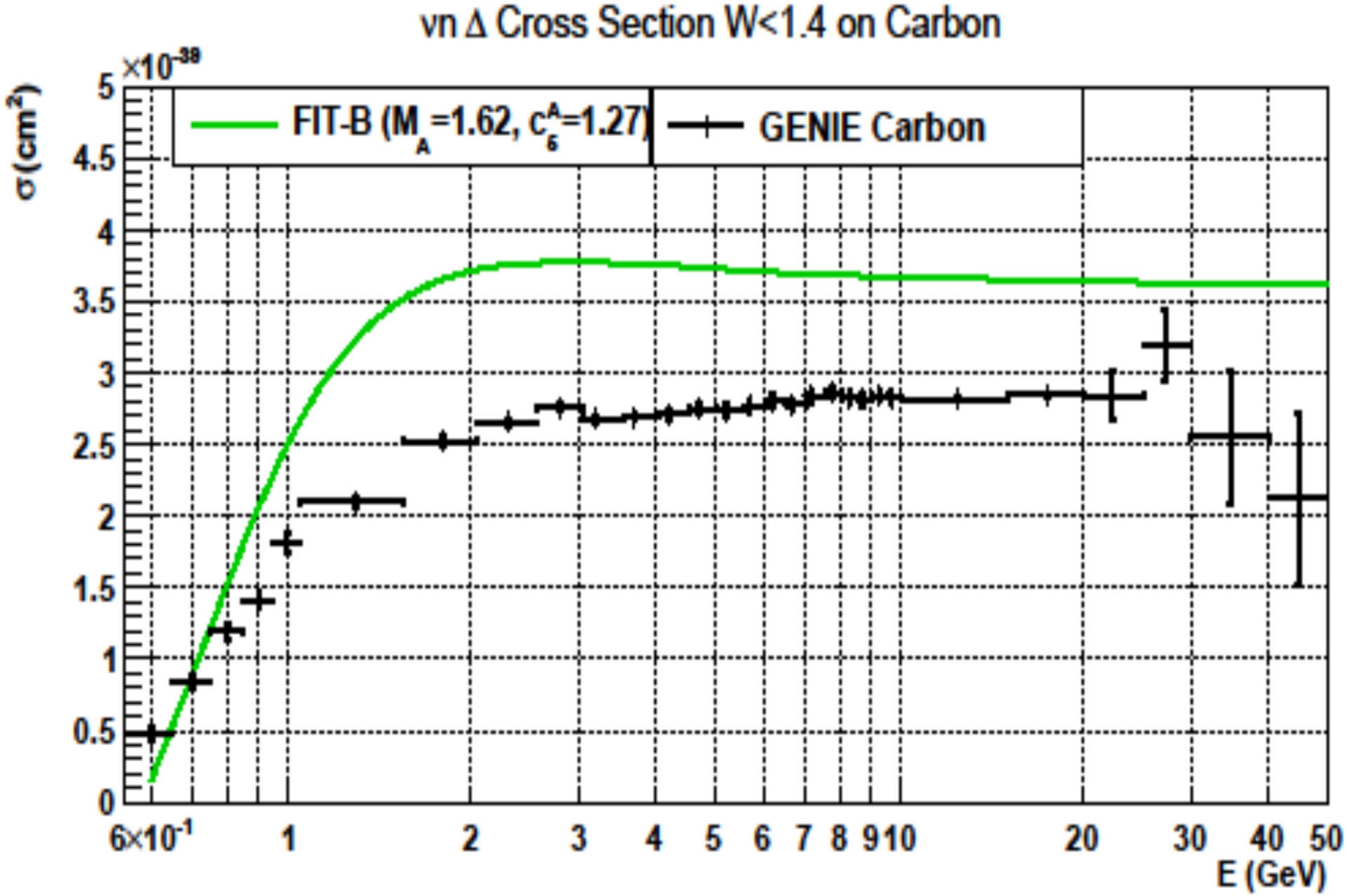
νp Delta Cross Section on Carbon



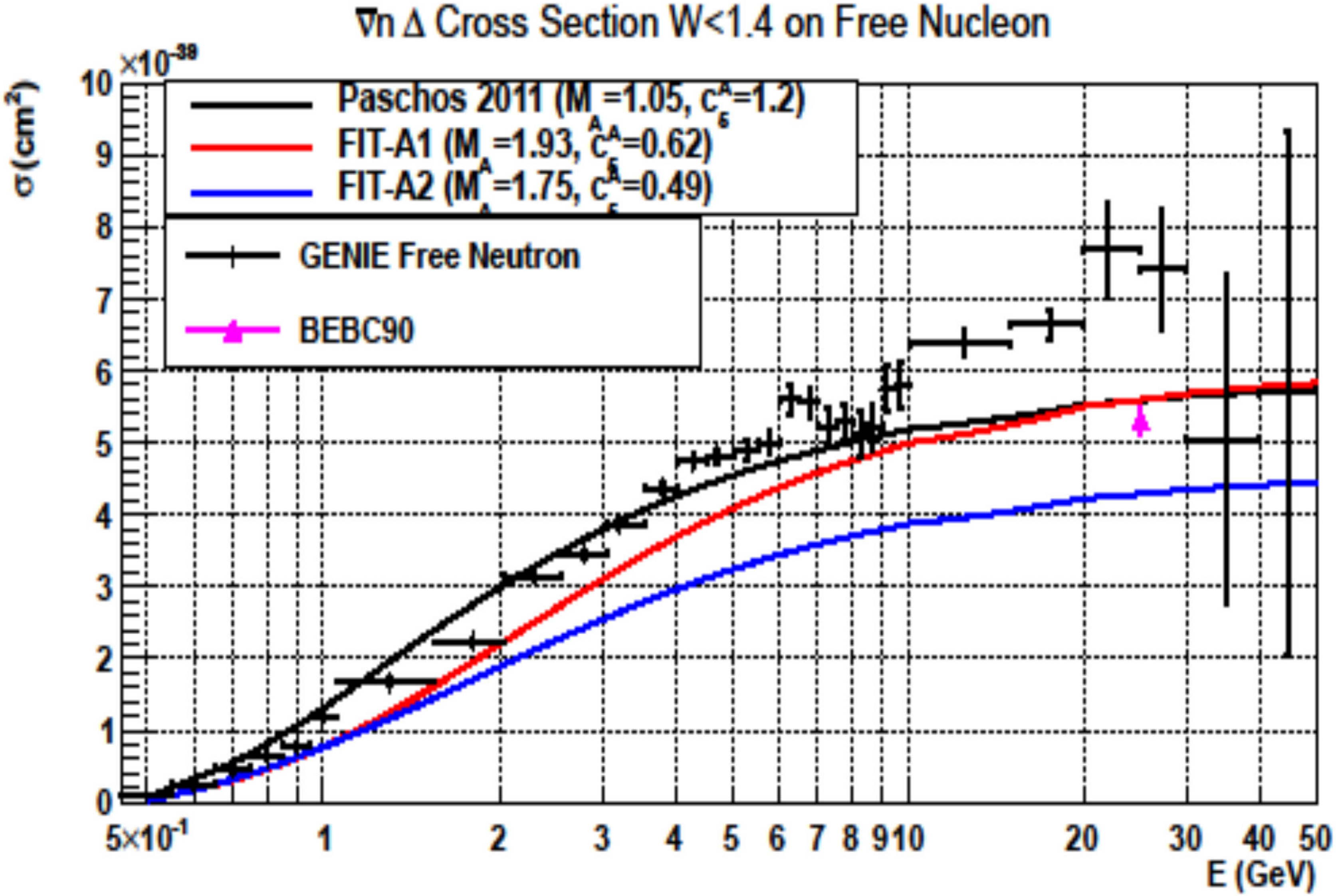
νn Delta Cross Section on Free Nucleon



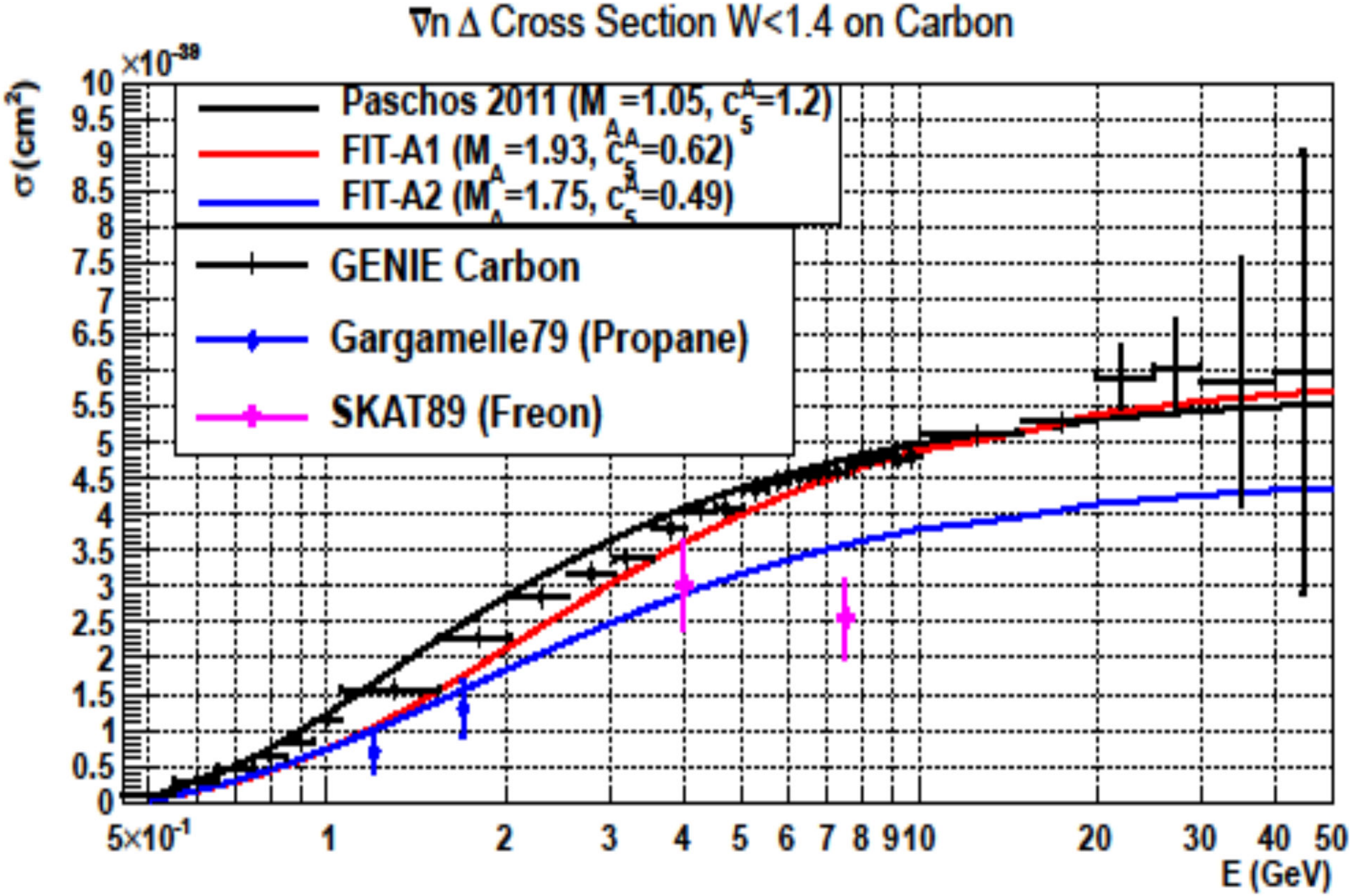
νn Delta Cross Section on Carbon



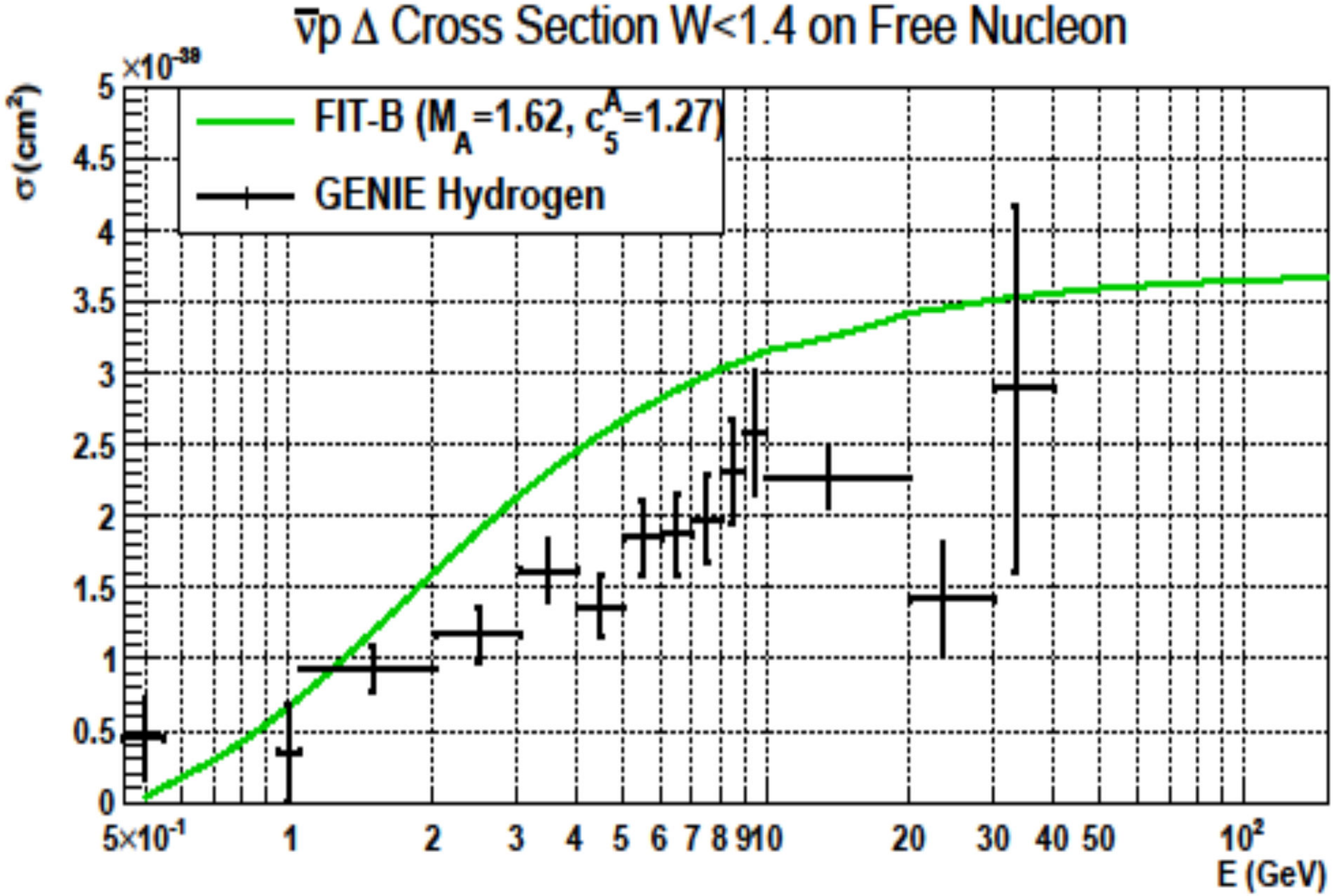
$\bar{\nu}n$ Delta Cross Section on Free Nucleon



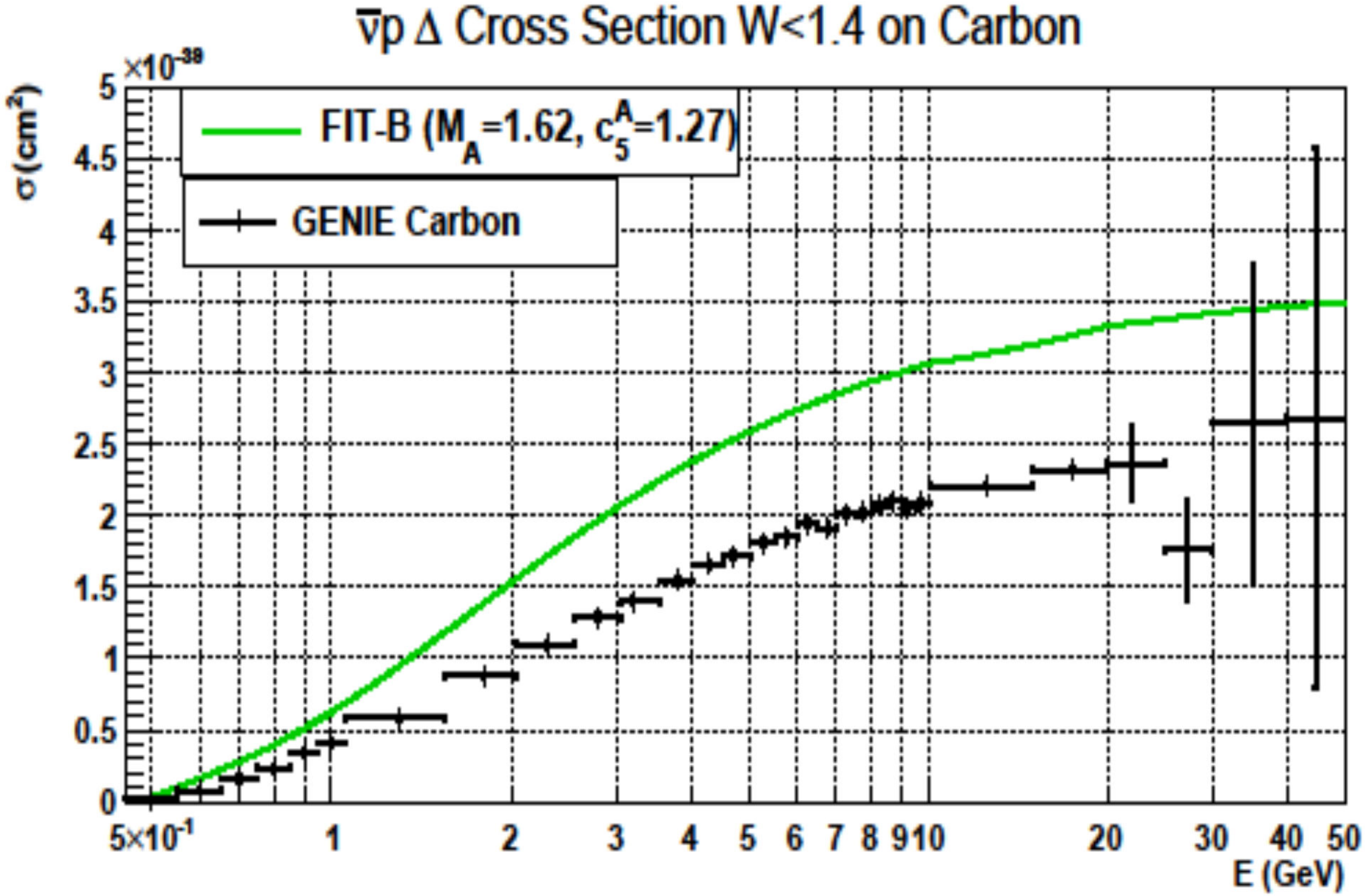
$\bar{\nu}n$ Delta Cross Section on Carbon



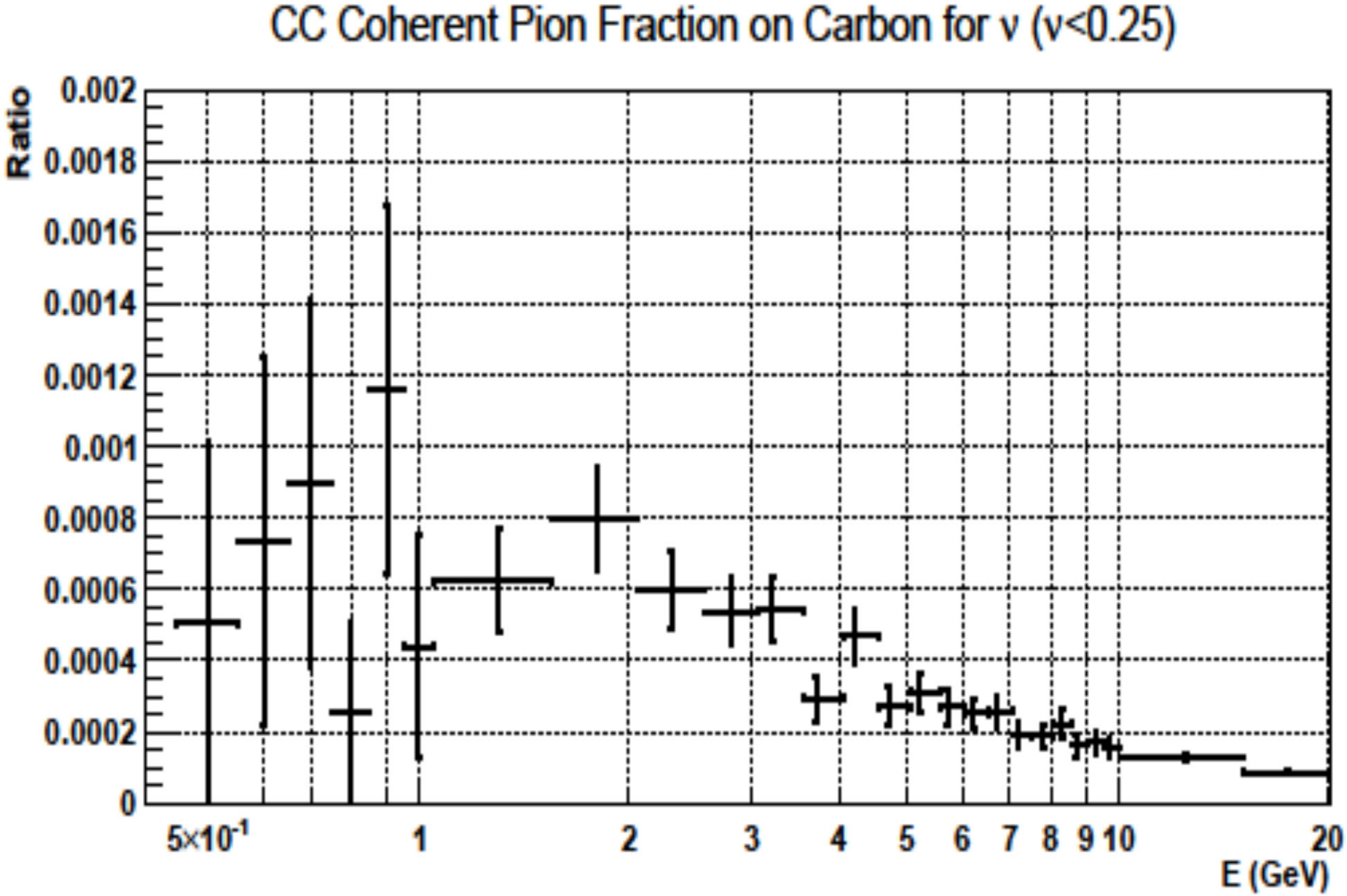
$\bar{\nu}p$ Delta Cross Section on Free Nucleon



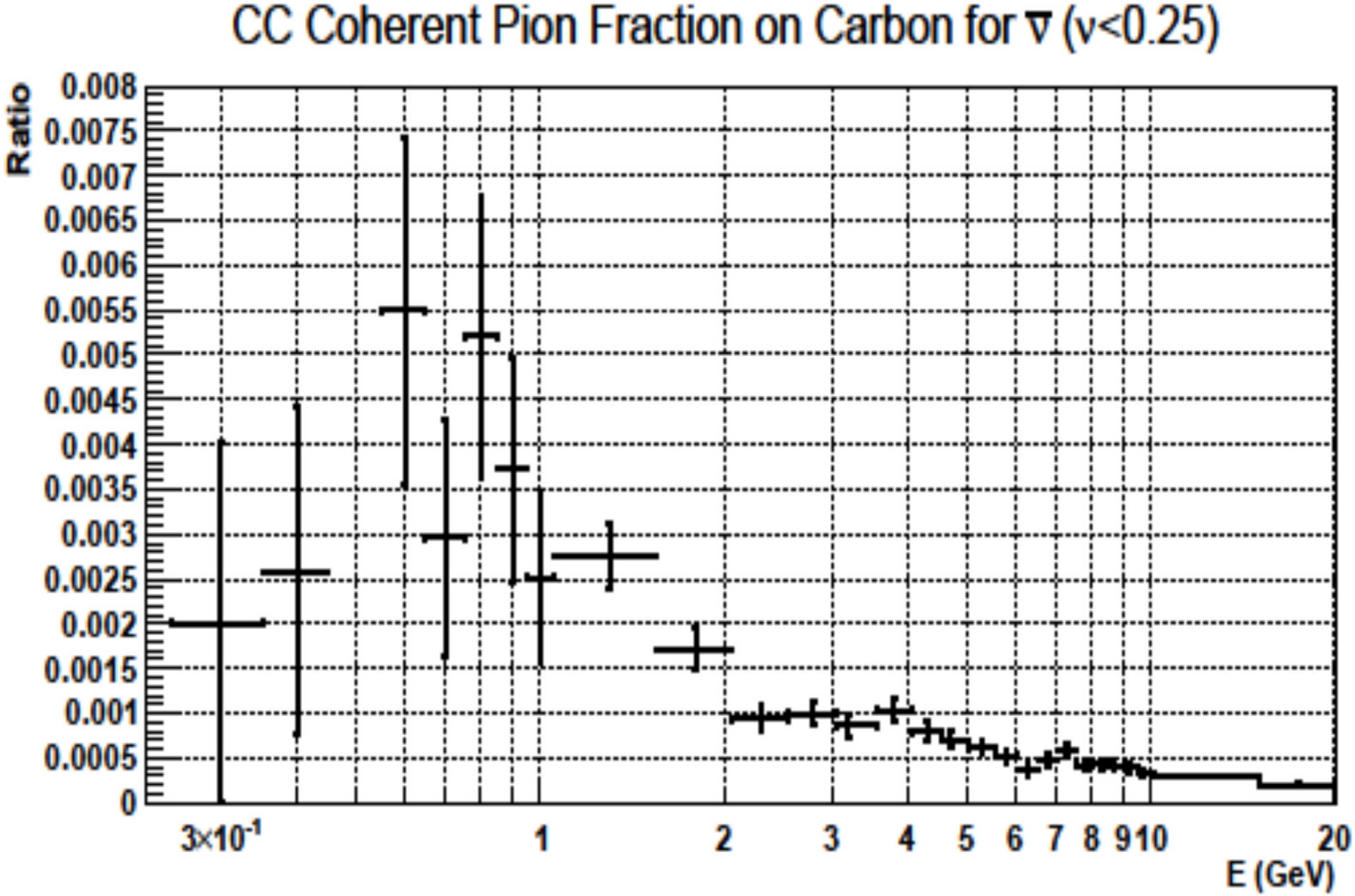
$\bar{\nu}$p Delta Cross Section on Carbon



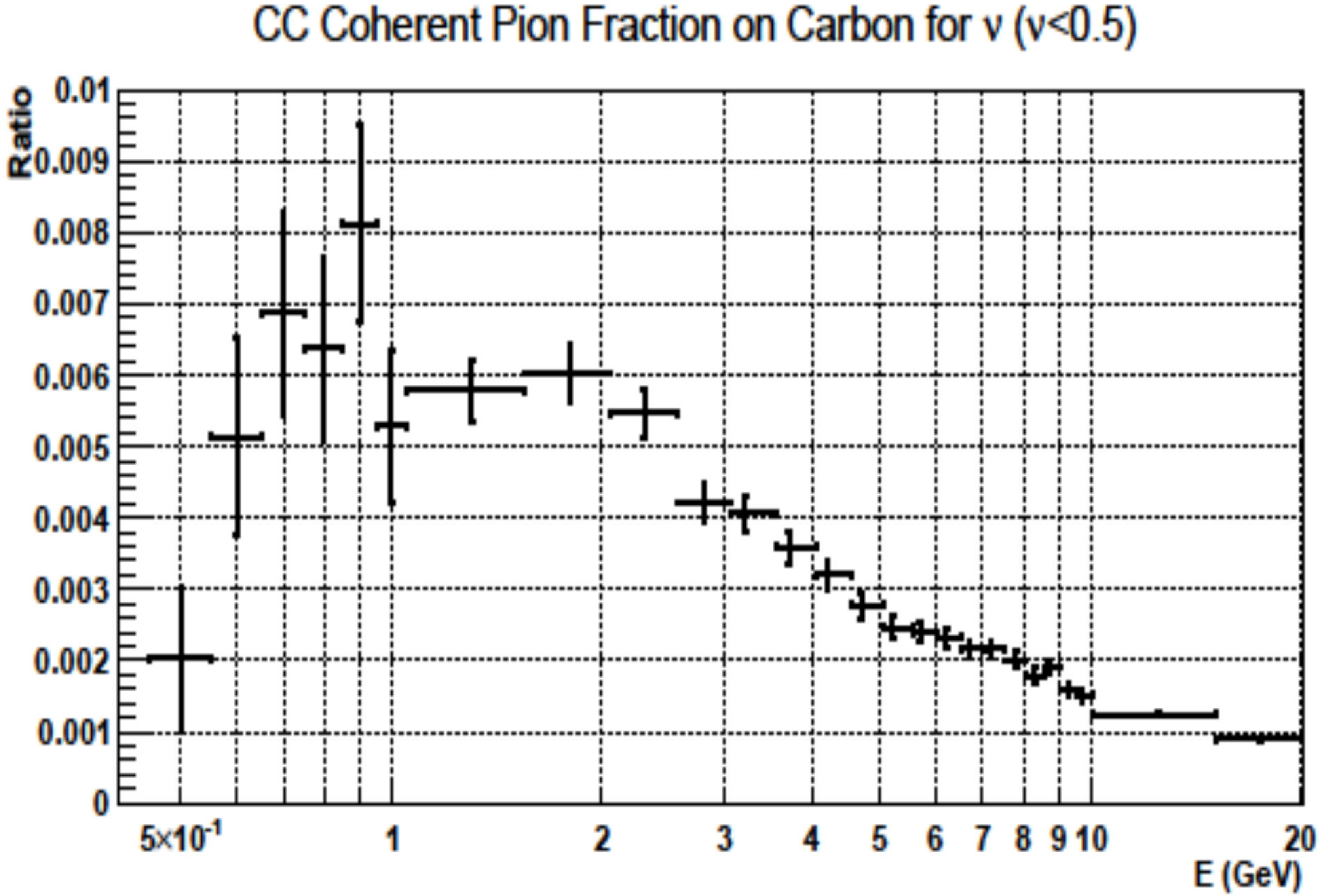
CC Coherent Fraction on Carbon for $\nu < 0.25\ GeV$



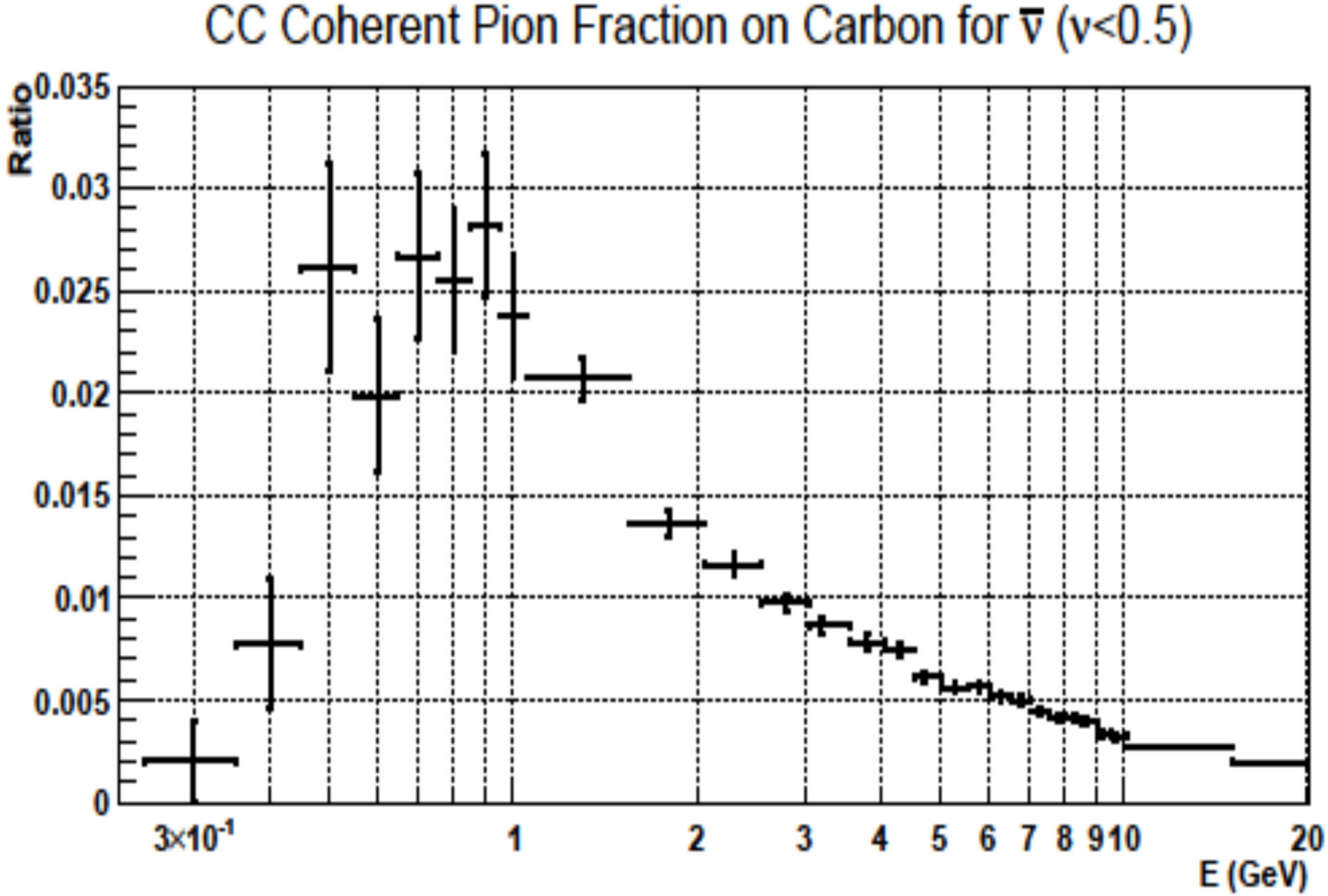
CC Coherent Fraction on Carbon for $\nu < 0.25\ GeV$



CC Coherent Fraction on Carbon for $\nu < 0.5\ GeV$



CC Coherent Fraction on Carbon for $\nu < 0.5\ GeV$



Additional References

[1] P. Adamson et al. Phys. Rev. Lett. 101. 131802. 4 (2008).

[2] Un Ki Yang, Ph.D. thesis, University of Rochester [FERMILAB-THESIS-2001-09, 2001].