Recent Developments in ν-A Interactions

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OUTLAY

Nuclear Effects in ν-A Cross Section

I. Quasielastic Reaction

II. Inelastic Reaction

Incoherent Pion Production

Coherent Pion Production

III. Deep-Inelastic Reaction

IV. Conclusion

Open Questions in ν Physics

• what are the masses of neutrinos?

• what is the mass hierarchy?

• more precisely measure remaining oscillation pars:

- what are the precise values of Δm^2_{12}, θ_{12}, $|\Delta m^2_{23}|$ and θ_{23}

- is θ_{13} non-zero?

• is CP violated in the sector?

•• if we want to address these questions, first need to understand how νs interact with matter ... to estimate signal, backgrounds

Various Nuclei being used or planned to be used in the different detectors

Nuclei	Detector	Experiments
$^{12}_{C}$	Scintillator,Mineral Oil	NOνA,MiniBooNE, K2K,MINERVA
$^{16}_{O}$	Water Cerenkov	T2K,SK-III,
		UNO,Hyper-K,K2K, MEMPHYS
$^{40}_{Ar}$	Liquid Argon TPC	ICARUS
$^{56}_{Fe}$	Iron Calorimeter	MINOS, INO, MINERVA
$^{208}_{Pb}$	Emulsion	OPERA,MINERVA

to see maximum osc effects
need to have low ν energy

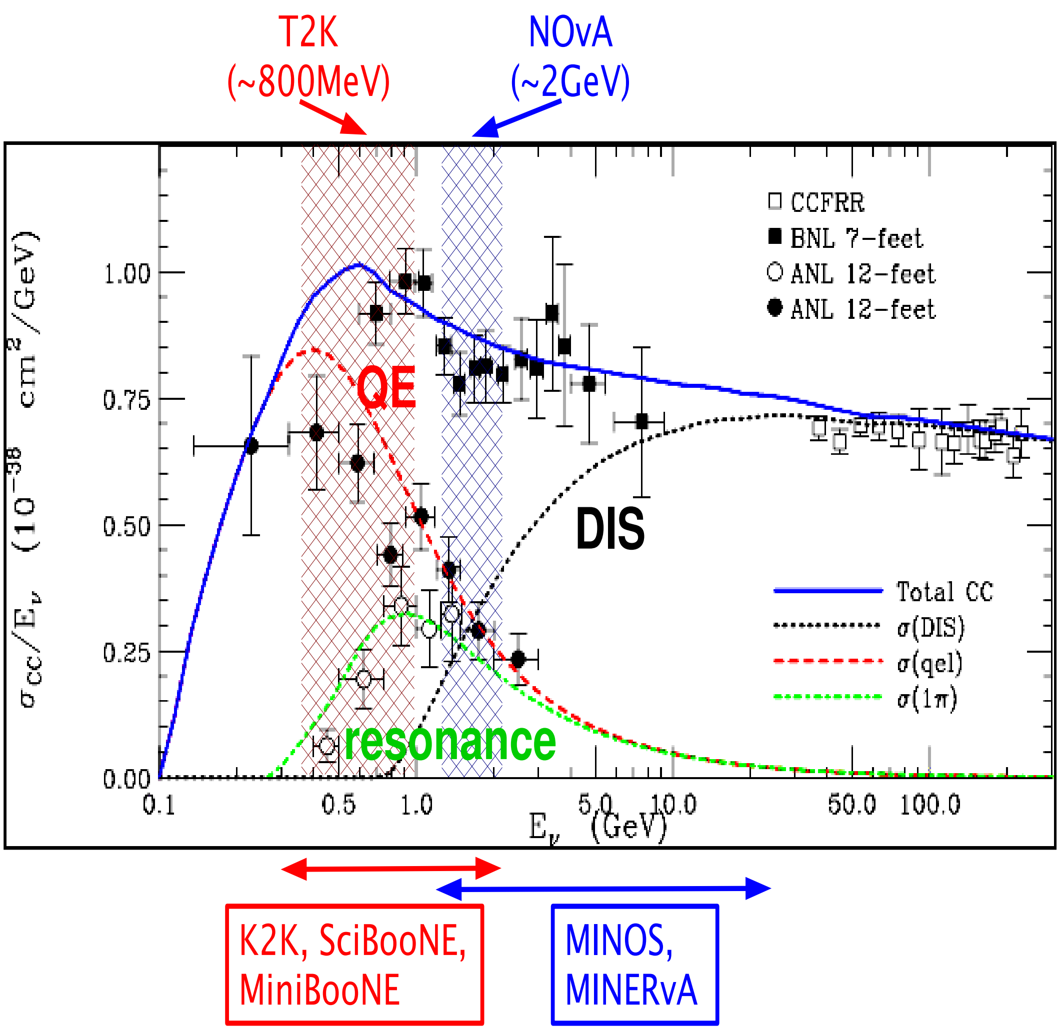
Energy Region of Interest

$$\mathbf{E}_\nu < \mathbf{3\ GeV}$$

At:

1. **K2K**
2. **MiniBooNE**
3. **T2K**
4. **β-Beam**
5. **Atmospheric**

P. Lipari, Nucl. Phys. B(PS) 112 (2002) 274



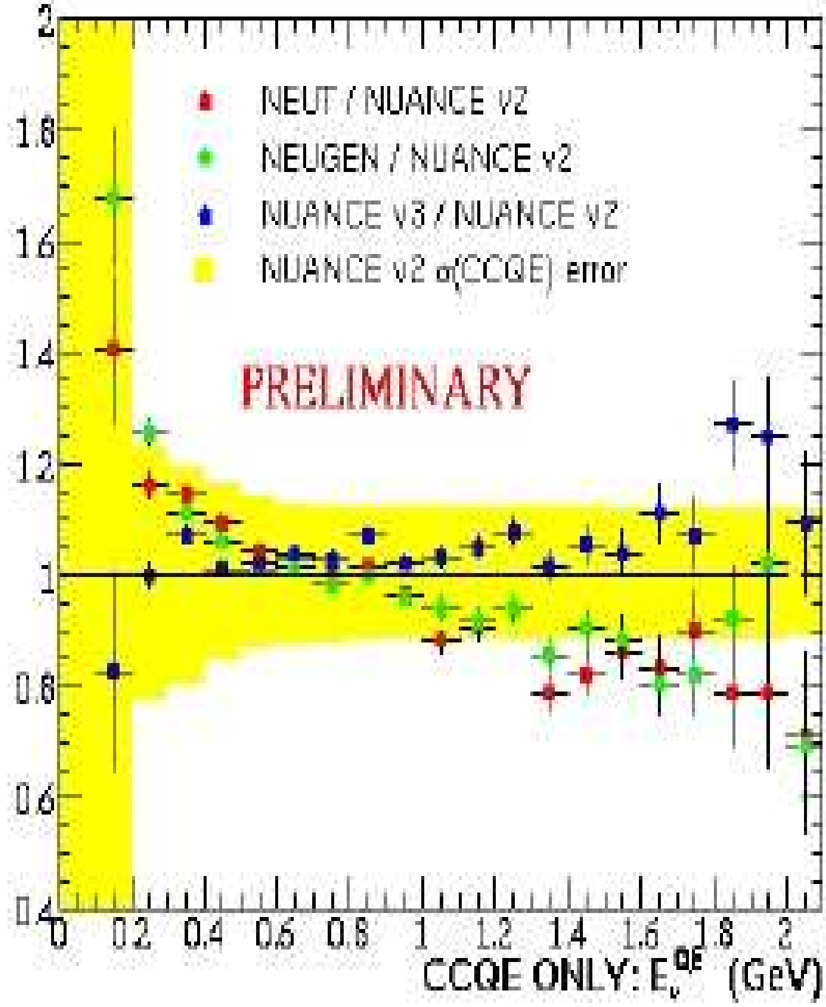
All the neutrino event generators use some nuclear model to estimate σ but inclusion of nuclear effects is mainly limited to Quasi Elastic reactions

Common Theoretical Inputs to all ν Event Generators:

- Llewellyn Smith free nucleon QE x-section
- Rein and Sehgal Resonance x-section
- Standard DIS formula for high W, Q^2.

Inputs which are different for various ν Event Generators:

√ Treatment of Nuclear Effects
√ Joining of Resonance and DIS
√ Treatment of FSI



NEUT / NUANCE v2
NEUGEN / NUANCE v2
NUANCE v3 / NUANCE v2
NUANCE v2 σ(CCQE) error
PRELIMINARY
CCQE ONLY: E_ν^{QE} (GeV)

Quasielastic Lepton Production

M. Sajjad Athar et al., AIP CP 981:240-242,2008;PRD75:09300
551 2006;EPJ A24:459-474,2005

J.A. Caballero et al. , nucl-th/0705.1429 (2007)

A. Butkevich, S. Kulagin, nucl-th/0705.1051 (2007)

K.S. Kim, L.E. Wright, nucl-th/0705.0049 (2007)

M. Martini et al., Phys. Rev. C75, 034604 (2007)

E. Hernandez et al. , PL B647, 452 (2007)

J.E. Amaro et al. , PRC 75, 034613 (2007)

C. Giusti et al., nucl-th/0607037 (2006)

O. Benhar et al., nucl-ex/0603029 (2006)

P. Lava et al., PRC 73, 064605 (2006)

R. Bradford et al., hep-ex/0602017 (2006)

K.S. Kuzmin et al., Acta Phys. Polon. B37, 2337 (2006)

J. Nieves et al., Phys. Rev. C73, 025504 (2006)

M.C. Martinez et al., PRC 73, 024607 (2006)

A. Meucci et al., Acta Phys. Polon, B27, 2279 (2006)

N. Jachowicz et al., NP. Proc. Suppl. 155, 260 (2006)

G. Co, ActaPhys.Polon.B37, 2235 (2006)

M. Valverde et al., PL B642, 218 (2006), PL B638, 325 (2006)

Inelastic Lepton and Pion Production

M. Sajjad Athar et al., NP A782, 179 (2007), PRD 75, 093003 (2007); PRD 74, 073008 (2006); PRL 96, 241802 (2006)

H. Nakamura et al., hep-ph/0705.3884 (2007)

E.A. Paschos et al., hep-ph/0704.1991 (2007)

O. Lalakulich, E.A. Paschos et al., Nucl. Proc. Suppl. 159, 133 (2006), PRD 74,014009 (2006)

O.Benhar, D. Meloni, PRL 97, 192301 (2006)

O. Buss et al., PRC 74, 044610 (2006), Eur. Phys. J. A29, 189 (2006)

L. Alvarez-Ruso et al., PRC 75, 055501 (2007)

E.A. Paschos, A. Kartavtsev, Nucl. Proc. Suppl. 159, 203 (2006), PRD 74, 054007 (2006)

D. Rein, L.M. Sehgal, hep-ph/0606185 (2006)

B.Z. Kopeliovich, Nucl. Phys. Proc. Suppl. 139, 219 (2006)

Deep-Inelastic Scattering

M. Sajjad Athar et al.,nucl-th/0711.4443(2007)

M. Hirai et al., Phys.Rev.C76:065207,2007.

S. Kulagin, R. Petti, hep-ph/0703033 (2007); NPA765:126-187,2006.

O. Lalakulich et al., PRC 75, 015202 (2007)

O. Benhar, D. Meloni, hep-ph/0610403 (2006)

K.S. Kuzmin et al., Phys. Atom. Nucl. 69, 1857 (2006)

L. Leitner et al., PRC 73, 065502 (2006), PRC 74, 065502 (2006), Int.J.Mod.Phys. A22, 416 (2007)

Quasielastic Charged Current Reaction

The basic ν_e-neutron reaction taking place in ^{A}X nucleus is

$$\nu_l(k) + n(p) \rightarrow l^-(k') + p(p')$$

The double differential cross section $\sigma_0(E_e, |\vec{k}'|)$

$$\sigma_0(E_e, |\vec{k}'|) = {G_F}^2 \cos^2\theta_c \frac{|\vec{k}'|^2}{8\pi E_{\nu_e} E_e} \frac{M_n M_p}{E_n E_p} \bar{\Sigma}\Sigma |T|^2 \delta[q_0 + E_n - E_p]$$

Matrix Element

$$T = \frac{G_F}{\sqrt{2}} \cos\theta_c \; l_\mu \; J^\mu$$

$$l_\mu = \bar{u}(k')\gamma_\mu(1-\gamma_5)u(k)$$

$$J^\mu = \bar{u}(p')\left[F_1^V(q^2)\gamma^\mu + F_2^V(q^2) i\sigma^{\mu\nu}\frac{q_\nu}{2M} F_A^V(q^2)\gamma^\mu\gamma_5 + F_P^V(q^2) q^\mu\gamma_5\right] u(p)$$

$F_1^V(q^2)$, $F_2^V(q^2)$, $F_A^V(q^2)$ and $F_P^V(q^2)$

are isovector form factors.

$F_1^V(0) = 1.0$, $F_2^V(0) = 3.7059$, Dipole mass $M_v = 0.84 GeV$, $F_A(0) = -1.26$.

$$F_1^V(q^2) = F_1^p(q^2) - F_1^n(q^2)$$

$$F_2^V(q^2) = F_2^p(q^2) - F_2^n(q^2)$$

$$F_A^V(q^2) = F_A(q^2)$$

$$F_1^{p,n}(q^2) = \left(1 - \frac{q^2}{4M^2}\right)^{-1} \left[G_E^{p,n}(q^2) - \frac{q^2}{4M^2} G_M^{p,n}(q^2)\right]$$

$$F_2^{p,n}(q^2) = \left(1 - \frac{q^2}{4M^2}\right)^{-1} \left[G_M^{p,n}(q^2) - G_E^{p,n}(q^2)\right]$$

where

$$G_E^p(q^2) = \left(1 - \frac{q^2}{M_V^2}\right)^{-2}$$

$$G_M^p(q^2) = (1 + \mu_p) G_E^p(q^2), \quad G_M^n(q^2) = \mu_n G_E^p(q^2)$$

$$G_E^n(q^2) = \left(\frac{q^2}{4M^2}\right) \mu_n G_E^p(q^2) \xi_n, \quad \xi_n = \frac{1}{1 - \lambda_n \frac{q^2}{4M^2}}$$

$$F_A(Q^2) = F_A(0) \left(1 - \frac{q^2}{M_V^2}\right)^{-2}$$

Deviations from the dipole behaviour have been discussed recently

P. E. Bosted, Phys. Rev. **C 51** (1995) 409.

H. Budd, A. Bodek and J. Arrington, Nucl. Phys. **B (PS)** 139 (2005) 90.

R. Bradford, H. Budd, A. Bodek and J. Arrington, Nucl. Phys. **B (PS)** 159 (2006) 127.

Axial dipole mass

$M_A = 1.03 GeV$ World Average

$M_A = 1.20 \pm 0.12 GeV$ K2K, SciFi, H_2O

$M_A = 1.14 \pm 0.11 GeV$ K2K, SciBar, ^{12}C

$M_A = 1.23 \pm 0.20 GeV$ MiniBooNE, ^{12}C

Local Density Approximation

The neutrino scatters from a neutron moving in the finite nucleus of neutron density $\rho_n(r)$, with a local occupation number $n_n(\mathbf{p},\mathbf{r})$, and σ is given by

$$\sigma_{Nucleus} = \int \rho_n(r) d^3 r [\sigma_{FreeNucleon}]$$

$$\rho_n(r) = 2 \int d\mathbf{p_n} \frac{1}{(2\pi)^3} n_n(\mathbf{p},\mathbf{r})$$

$$\sigma(E_e, |\vec{k}'|) = \int 2 d\mathbf{r} d\mathbf{p} \frac{1}{(2\pi)^3} n_n(\mathbf{p},\mathbf{r}) \sigma_0(E_e, k')$$

$$\begin{aligned} \sigma_0(E_e, |\vec{k}'|) \;\; = \;\; & {G_F}^2 \cos^2\theta_c \frac{|\vec{k}'|^2}{8\pi E_{\nu_e} E_e} \frac{M_n M_p}{E_n E_p} \\ & \bar{\Sigma}\Sigma |T|^2 \delta[q_0 + E_n - E_p] \end{aligned}$$

We take into account:

(i) Pauli blocking and Fermi motion of the nucleons

(ii) Q-value of the reaction

(iii) Coulomb distortion of the charged leptons in an effective momentum approximation

(iv) Medium polarization effects in an Random Phase Approximation(RPA) which includes the particle hole and Δ-hole degrees of freedom

Thus, in presence of nuclear medium effects $\sigma(E_\nu)$ is given by

$$\sigma^{FF(MEMA)}(E_\nu) = -\frac{2{G_F}^2 \cos^2\theta_c}{\pi}\int_{r_{min}}^{r_{max}} r^2 dr$$

$$\times \int_{{p_e}^{min}}^{{p_e}^{max}} {p_e}^2 dp_e \int_{-1}^{1} d(cos\theta)$$

$$\times \frac{1}{E_{\nu_e}E_e} L_{\mu\nu} J^{\mu\nu}_{RPA} Im{U_N}^{FF(MEMA)}.$$

where

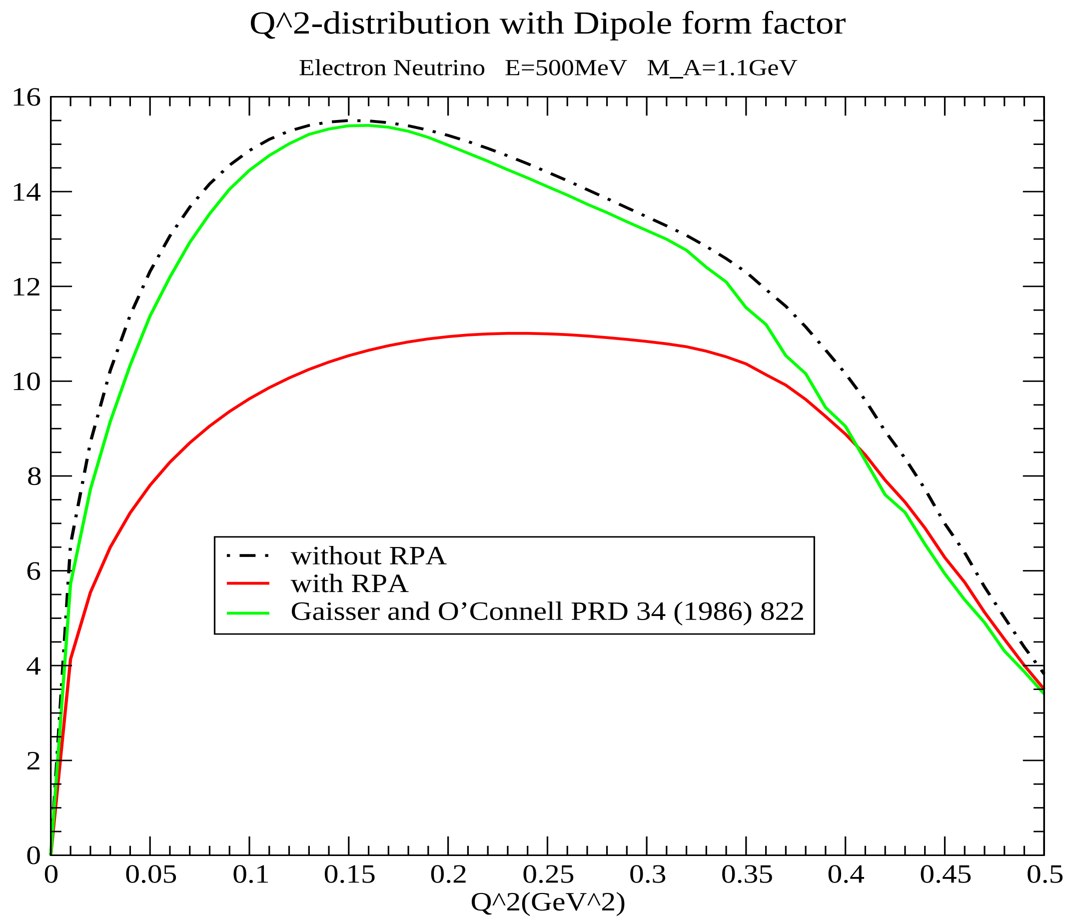
$$ImU_N^{FF} = F(Z,E_e) ImU_N[E_{\nu_e} - E_e - Q, \vec{q}]$$

$$\mathrm{ImU}_N^{MEMA} = ImU_N[E_{\nu_e} - E_e - Q - V_c(r), \vec{q}]$$

Results

Intermediate Energy ν-A Reaction

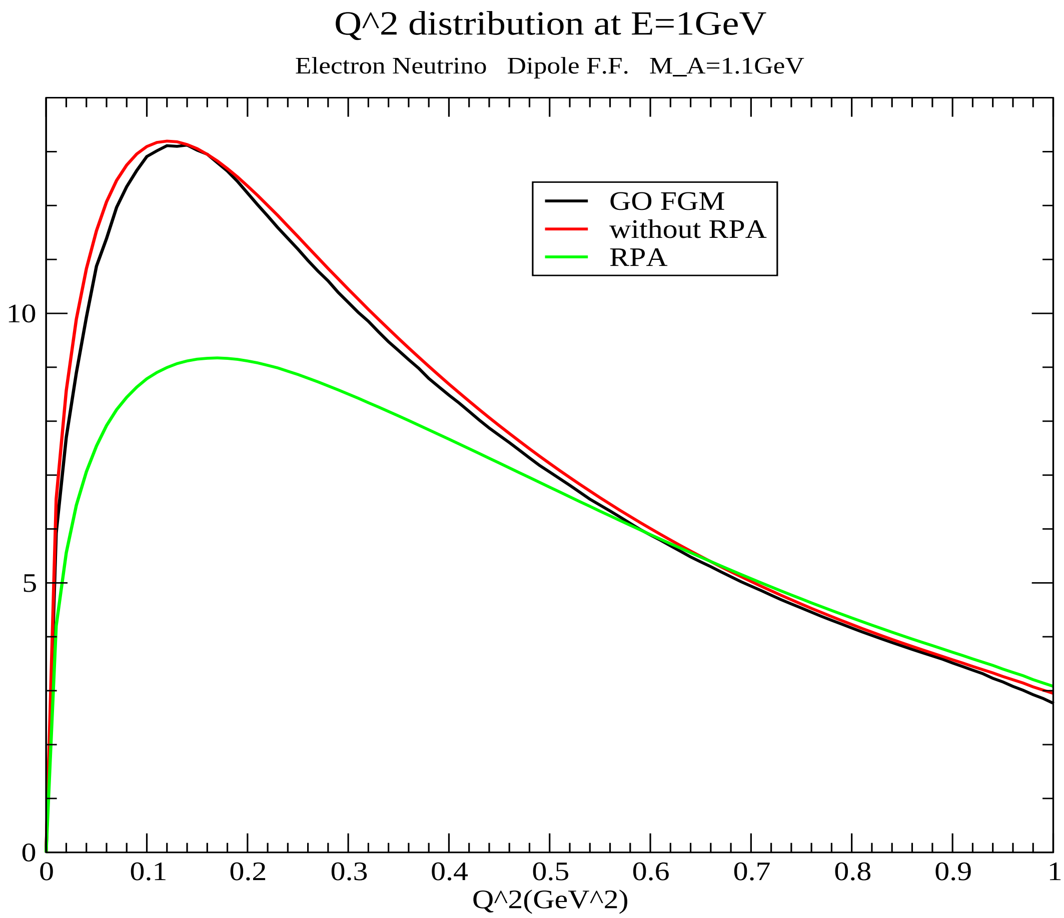
$\frac{d\sigma}{dQ^2}$ vs Q^2 in $10^{-38} \frac{cm^2}{GeV^2}$ in $\nu_e + ^{16}O$ scattering



Q^2(GeV^2)	with RPA
0.1	70
0.15	32
0.2	28
0.3	19
0.5	8

% reduction in the Q^2 distribution when RPA is encorporated

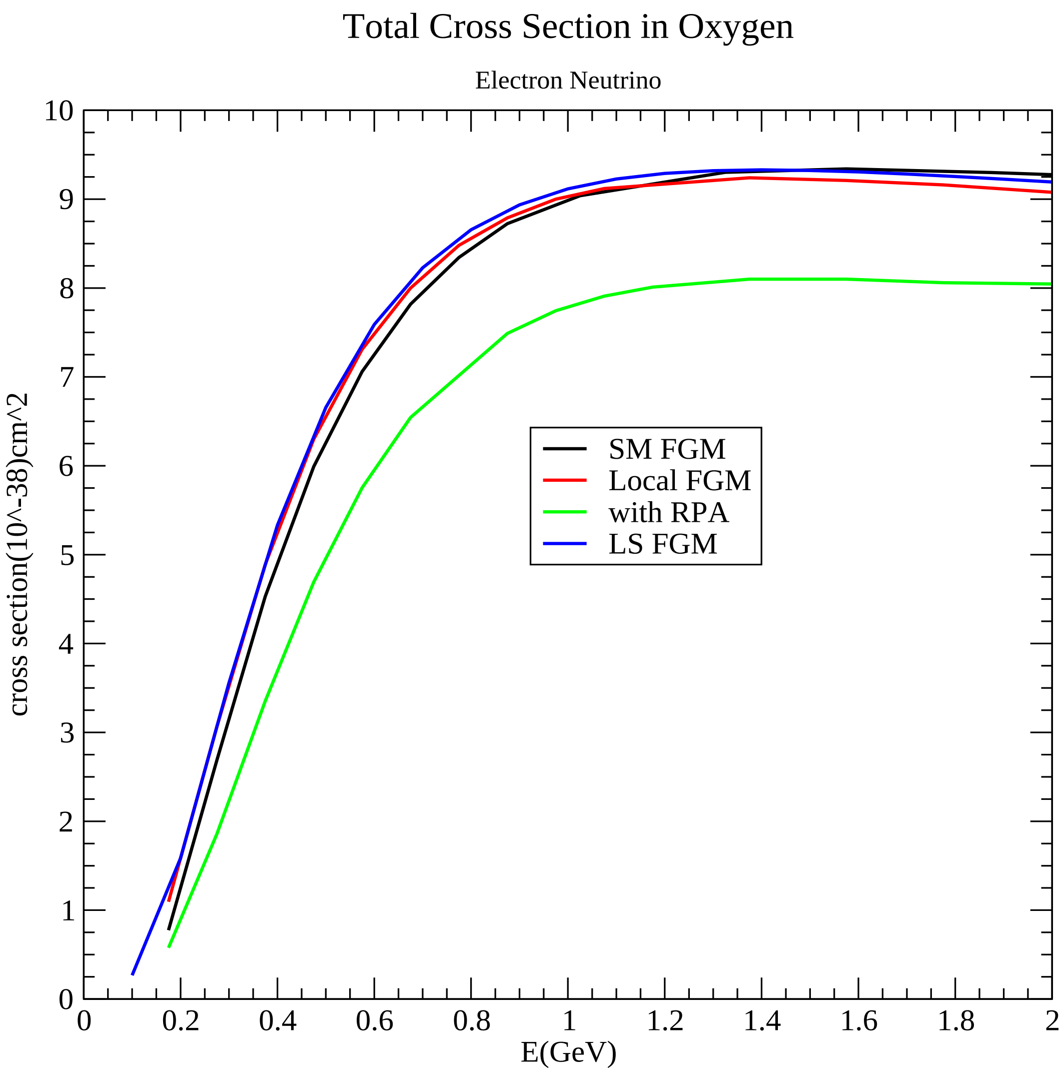
$\frac{d\sigma}{dQ^2}$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_e +^{16} O$ scattering



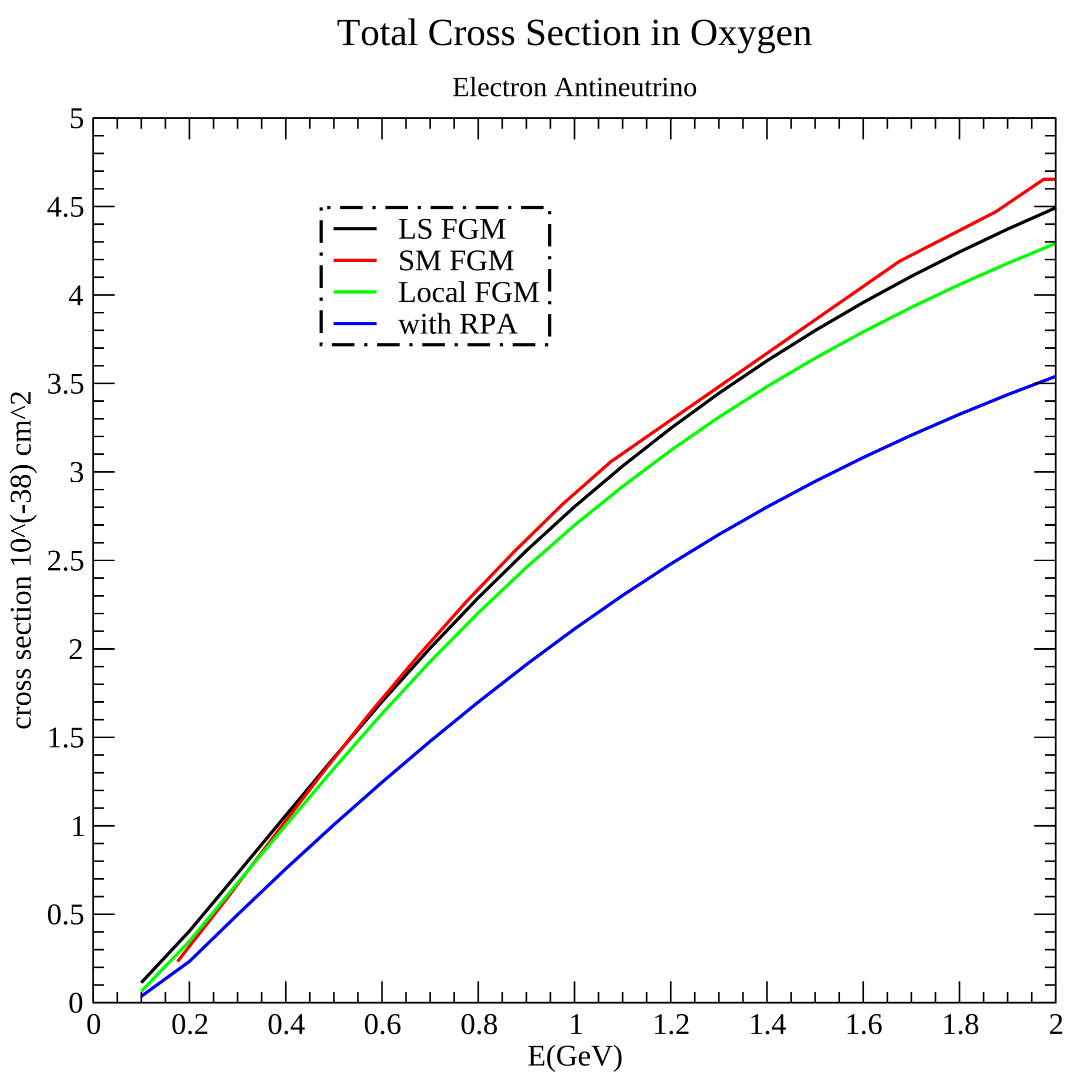
Q^2(GeV^2)	with RPA
0.1	33
0.15	30
0.2	26
0.3	18
0.5	6

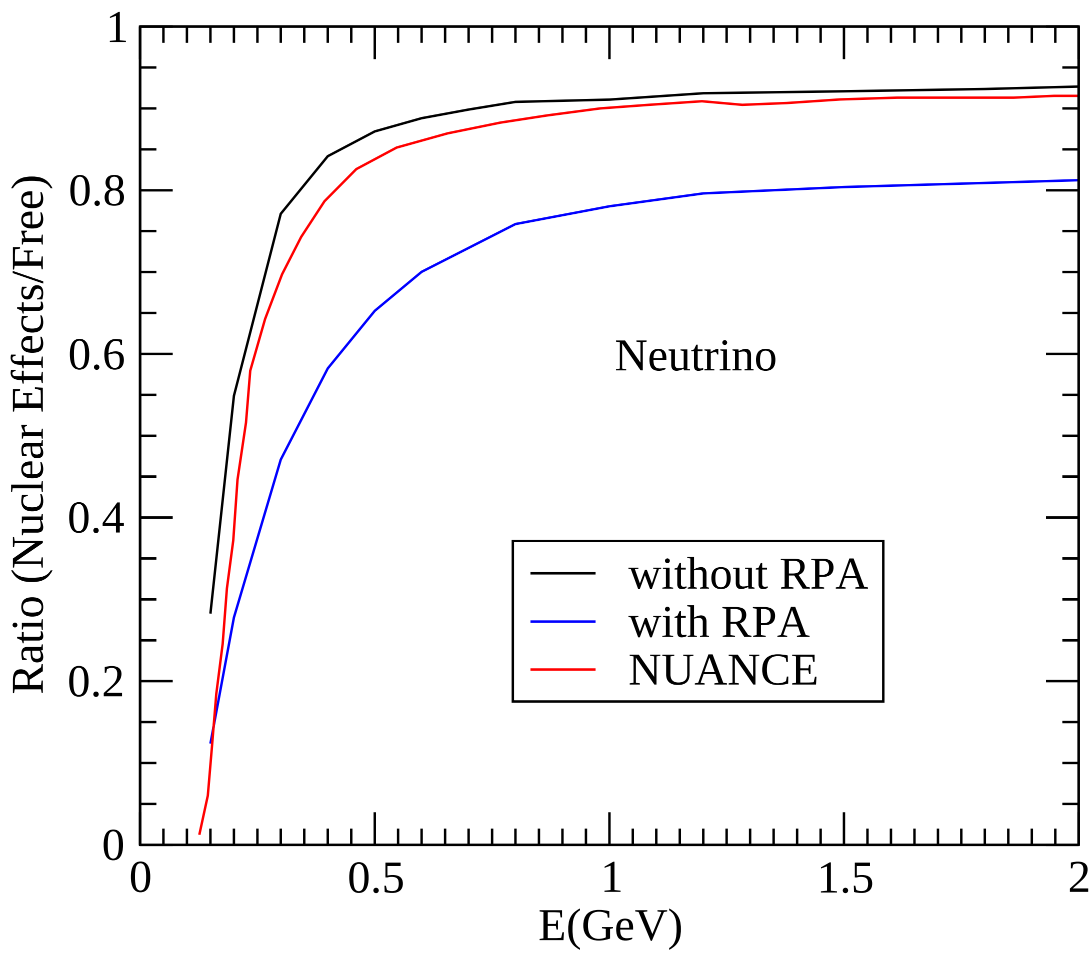
% reduction in the Q^2 distribution when RPA is encorporated

σ vs E_{ν_e} in $10^{-38} cm^2$ in $\nu_e + ^{16}O$ scattering



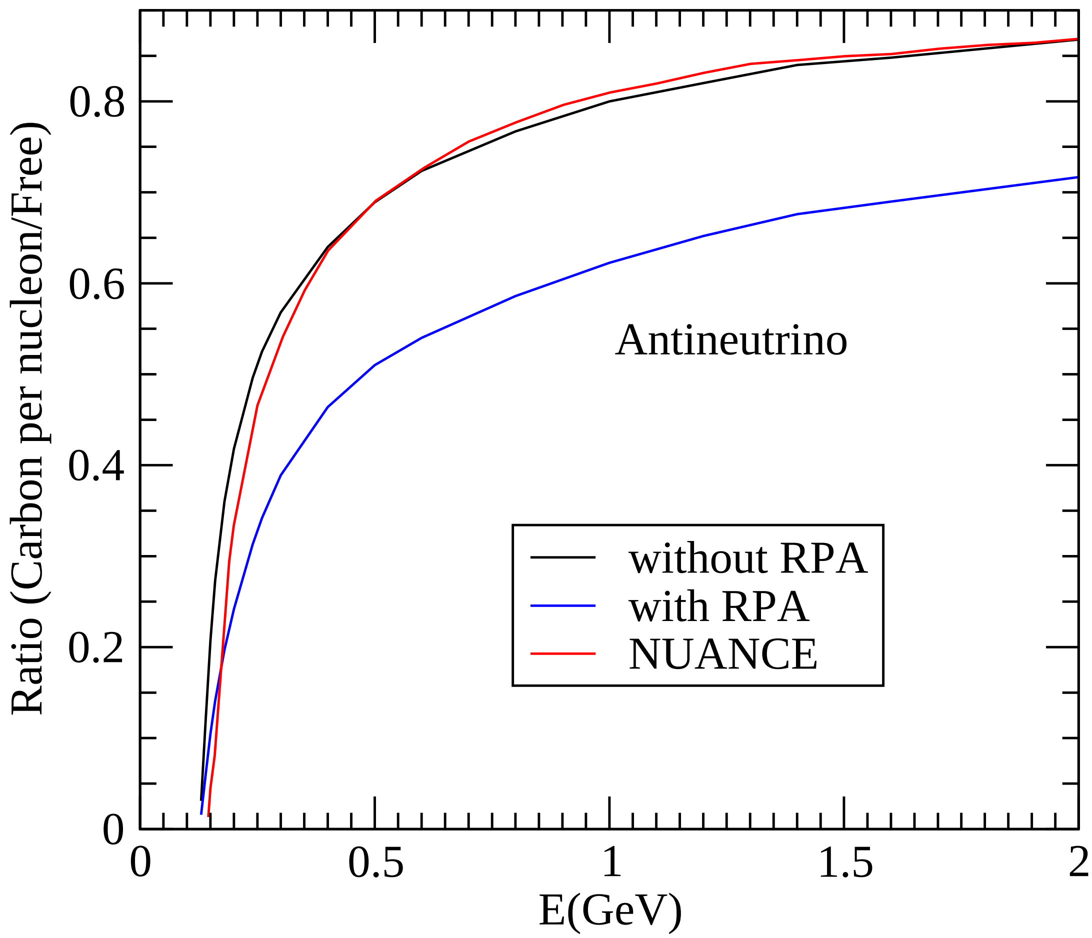
σ vs $E_{\bar{\nu}_e}$ in $10^{-38} cm^2$ in $\bar{\nu}_e + ^{16}O$ scattering





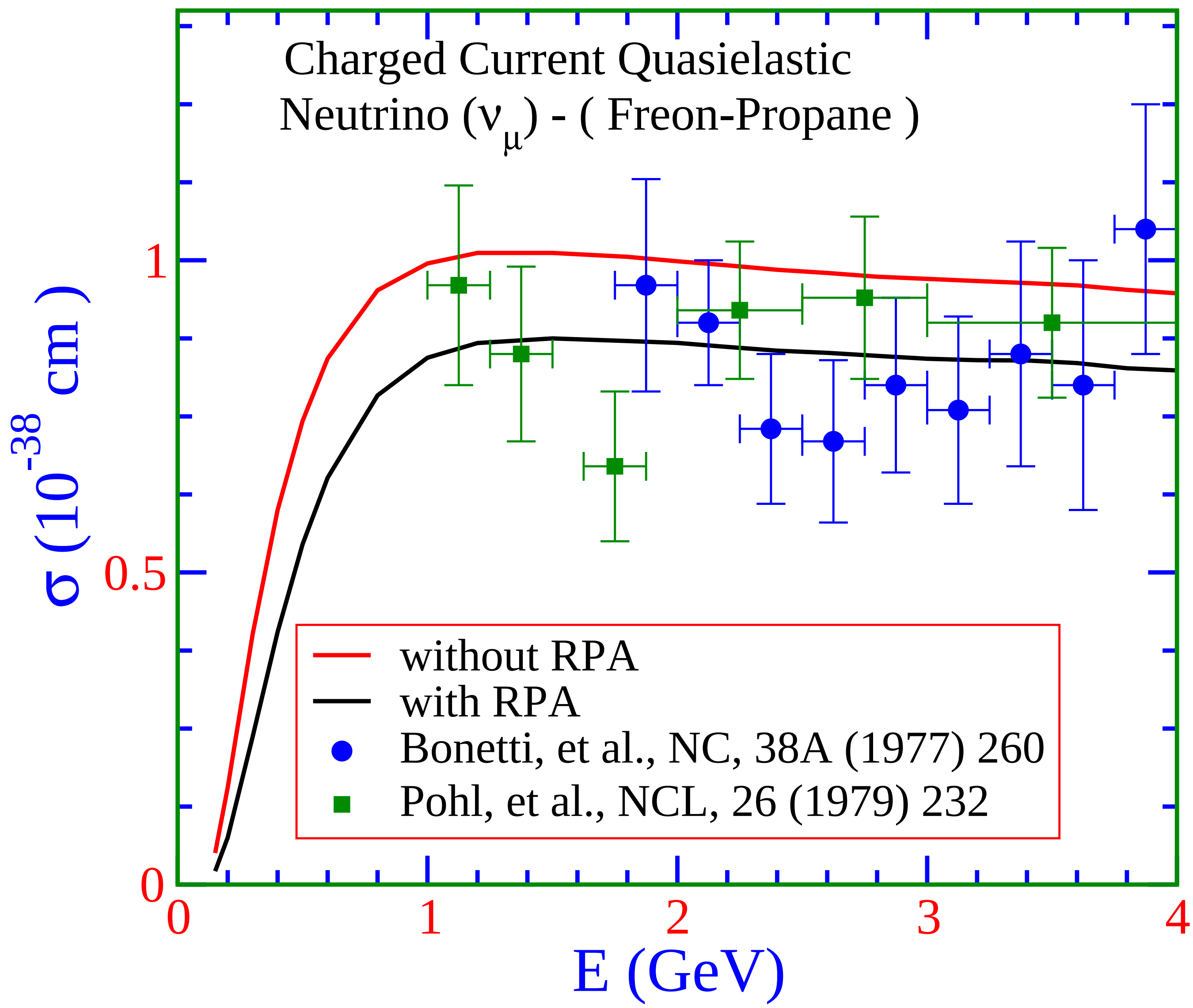
% reduction in the total cross section σ

$E_\nu(MeV)$	FGM	with RPA
200	45	72
400	16	42
1000	9	22
1500	8	20
2000	7	18

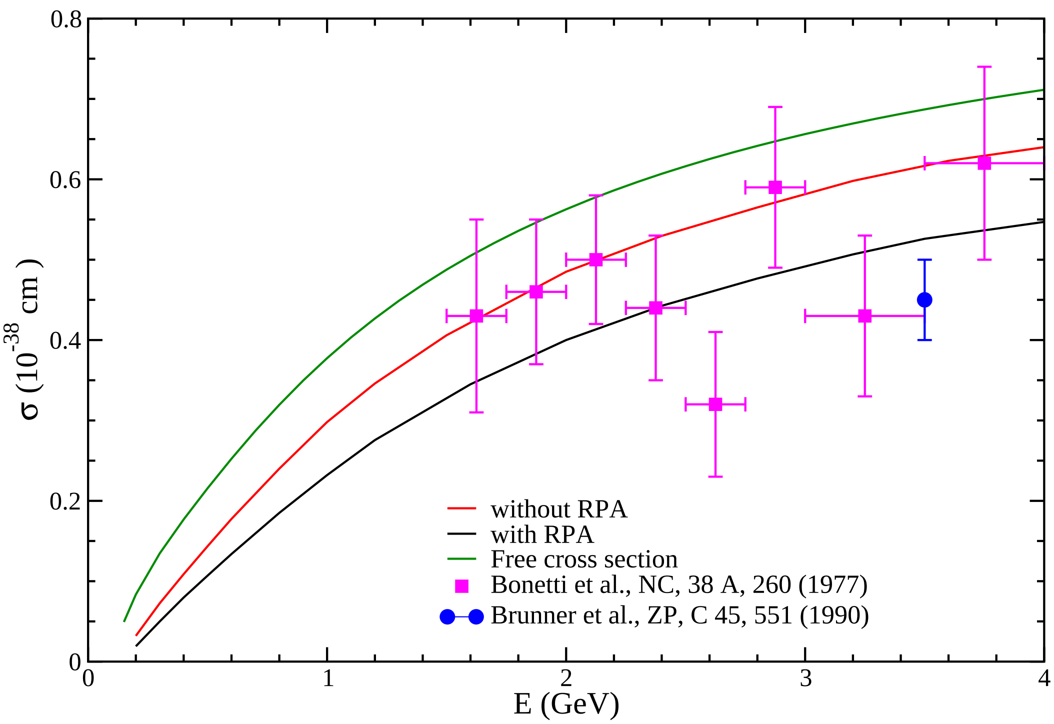


% reduction in the total cross section σ

$E_\nu(MeV)$	without RPA	with RPA
200	60	75
400	36	54
1000	20	38
1500	16	32
2000	12	28

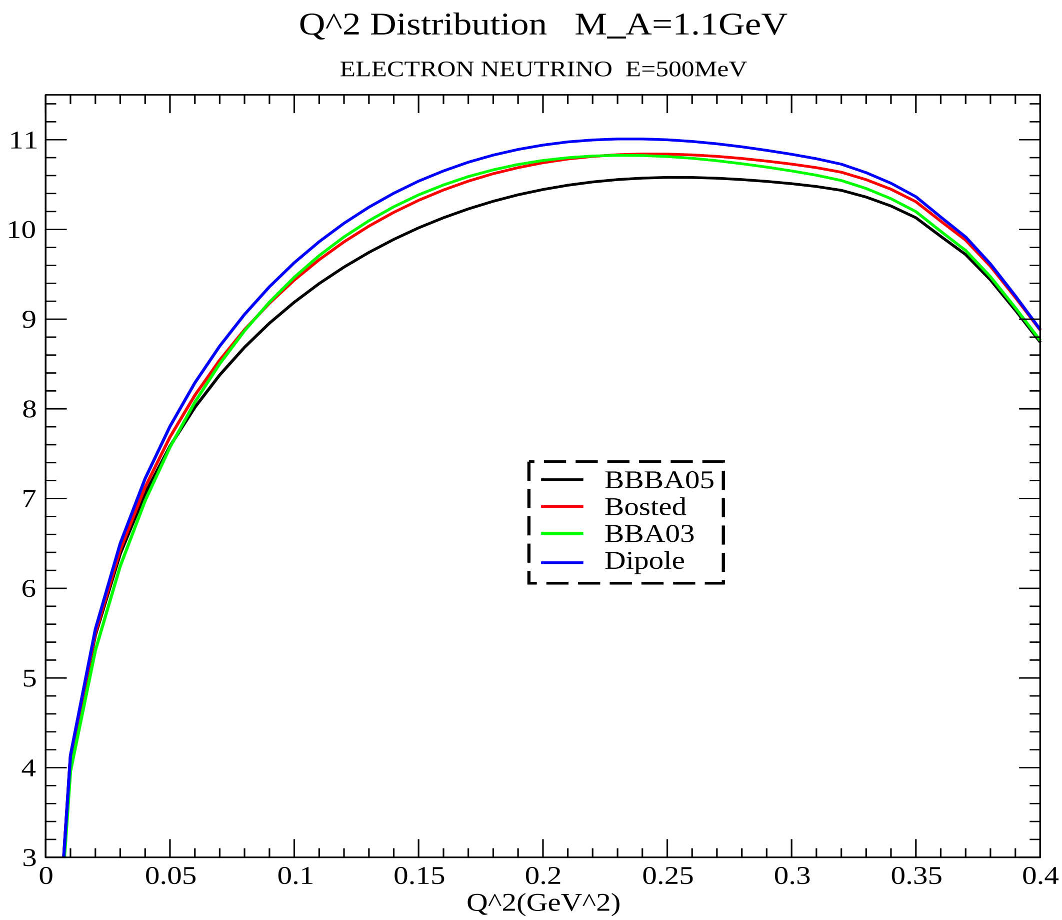


Charged Current Quasielastic
Neutrino (ν_μ) - (Freon-Propane)
σ (10^{-38} cm)
E (GeV)
without RPA
with RPA
Bonetti, et al., NC, 38A (1977) 260
Pohl, et al., NCL, 26 (1979) 232
0
0.5
1
0
1
2
3
4



Antineutrino reaction cross section on Freon

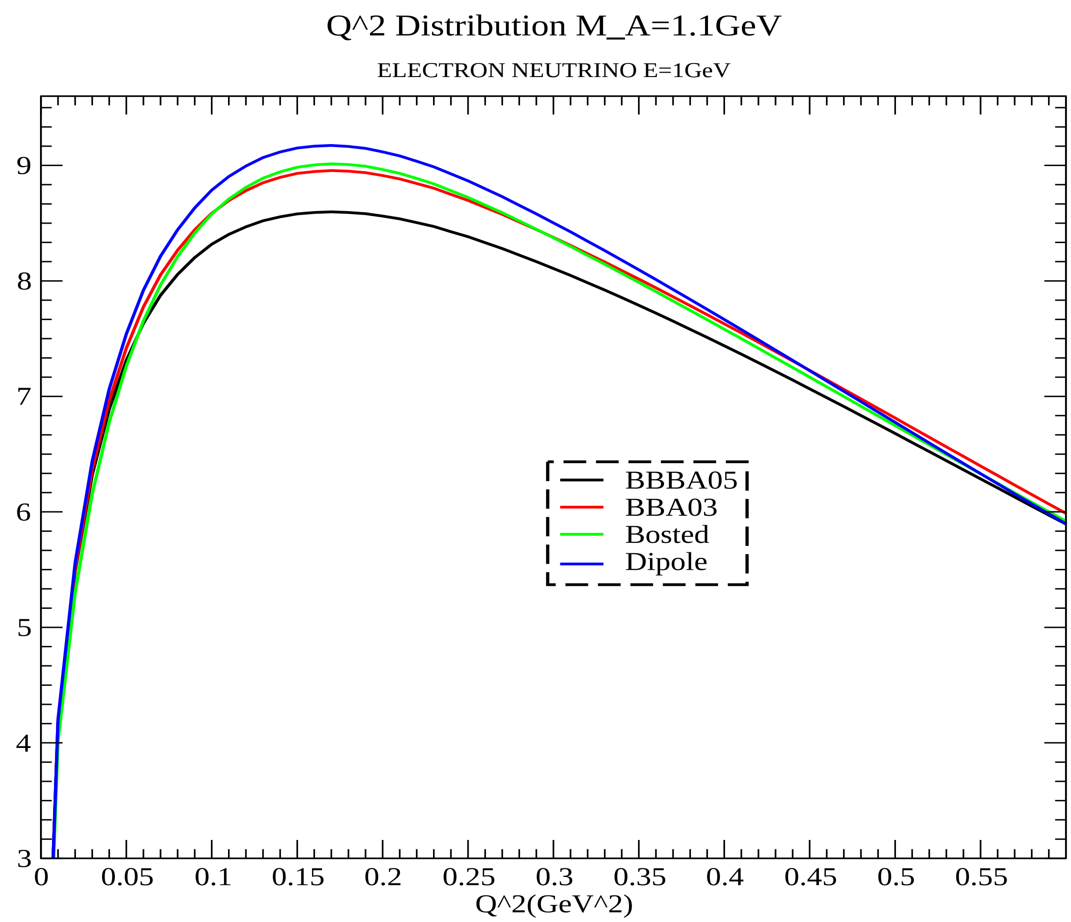
$\frac{d\sigma}{dQ^2}$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_e + ^{16}O$ scattering



Q^2(GeV^2)	BBBA05	BBA03	Bosted
0.05	2.8	1.5	2.9
0.25	3.8	1.4	1.7
0.5	0.34	–	0.68

% reduction in the Q^2 distribution as compared to Dipole

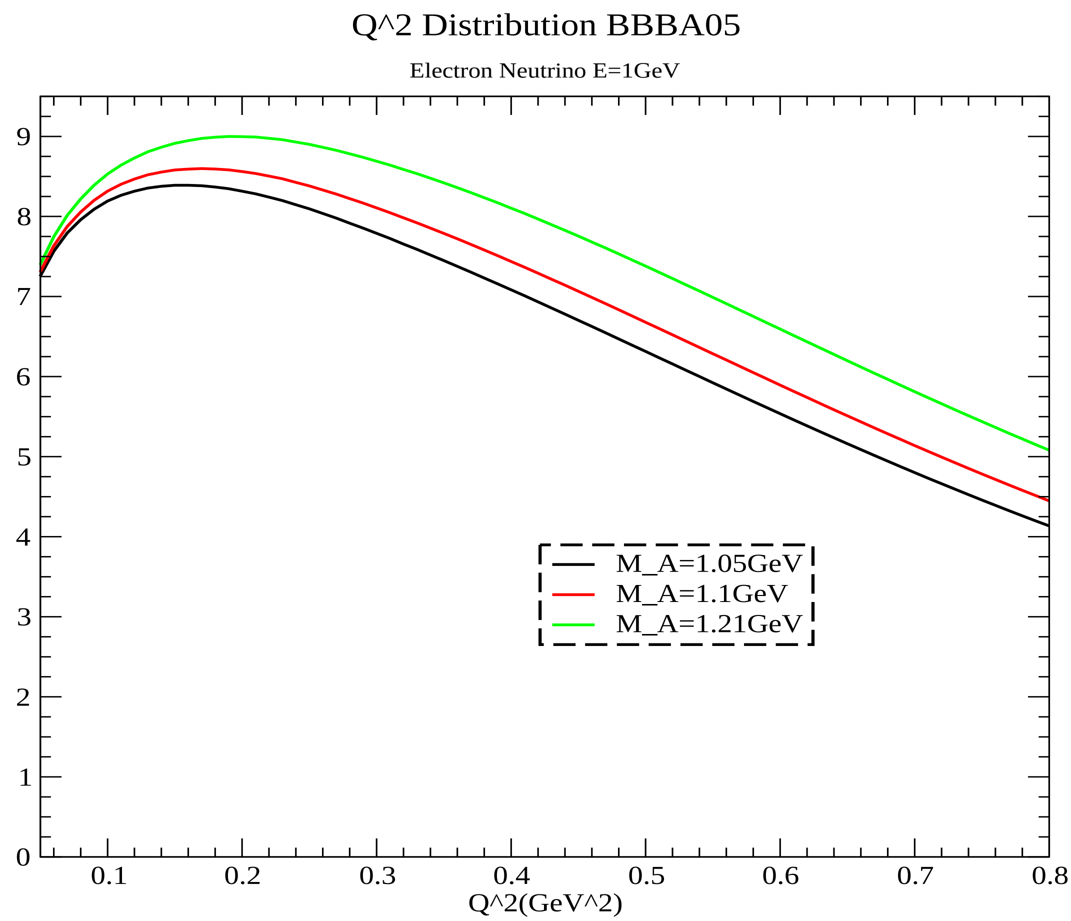
$\frac{d\sigma}{dQ^2}$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_e +^{16} O$ scattering



Q^2(GeV^2)	BBBA05	BBA03	Bosted
0.05	3	1.5	<0.5
0.17	6.2	2.2	1.7
0.4	3	<0.5	1

% reduction in the Q^2 distribution as compared to Dipole

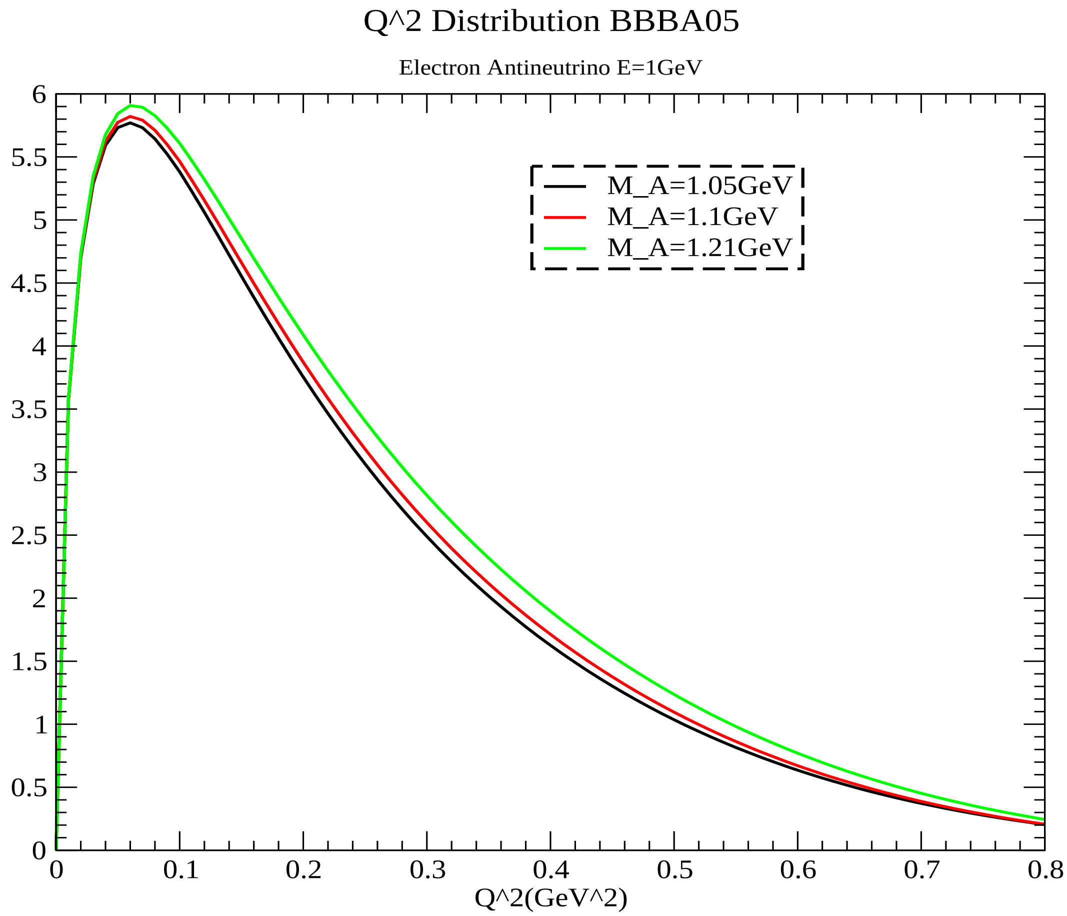
$\frac{d\sigma}{dQ^2}$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_e + ^{16}O$ scattering



Q^2(GeV^2)	M_A=1.05	M_A=1.21GeV
0.1	1.5	2.5
0.2	2.9	5.0
0.3	7.1	7.0
0.5	5.4	10.5
0.7	6.6	13.0

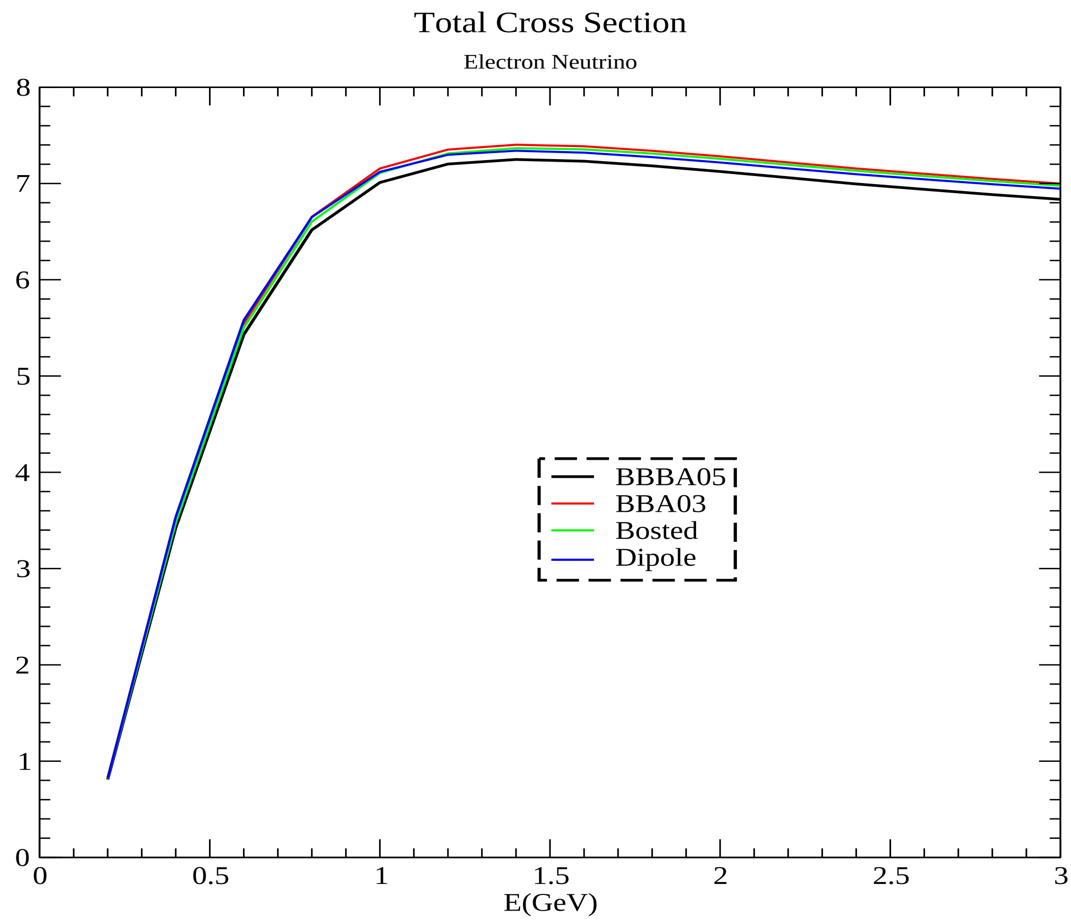
% change in the Q^2 distribution as compared to M_A=1.1GeV

$\frac{d\sigma}{dQ^2}$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\bar{\nu}_e +^{16} O$ scattering



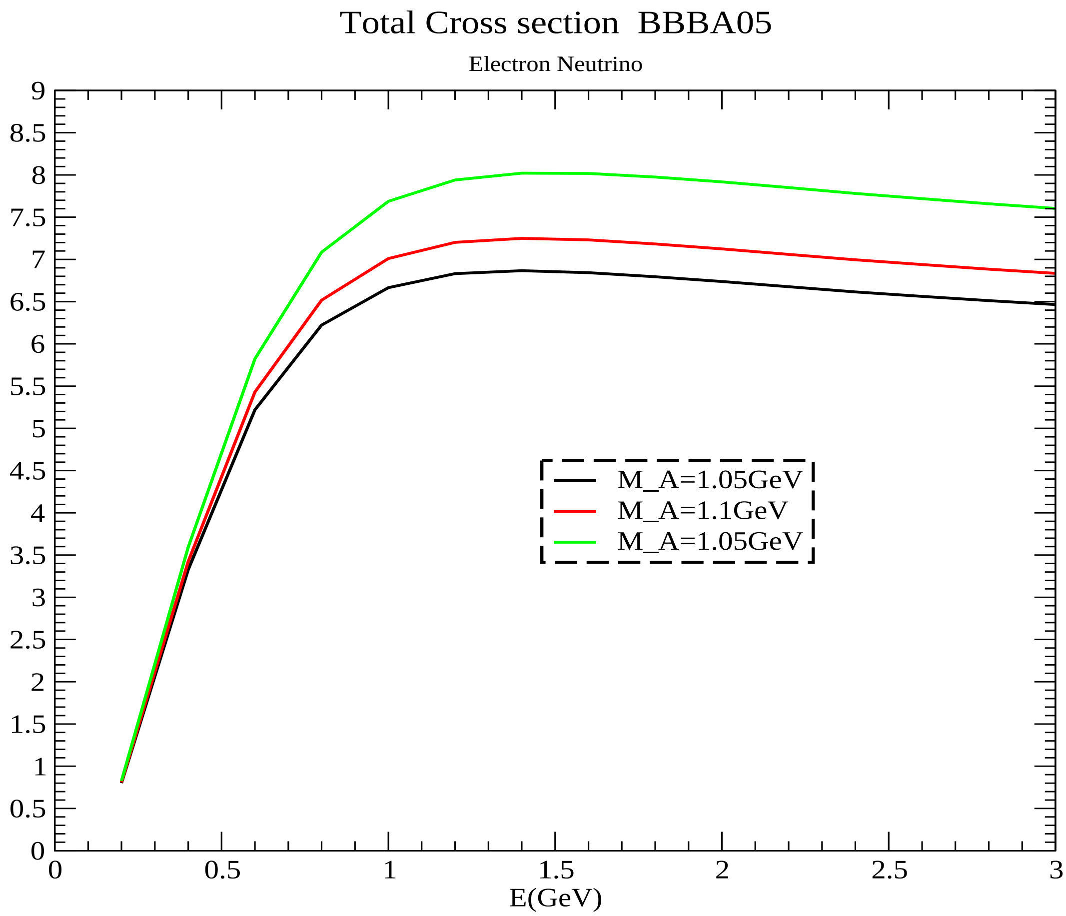
Q^2(GeV^2)	M_A=1.05	M_A=1.21GeV
0.05	0.7	1.2
0.1	1.5	2.6
0.2	3.0	5.5
0.3	4.3	8.3

% change in the Q^2 distribution as compared to M_A=1.1GeV



E(GeV)	BBBA05	BBA03	Bosted
0.6	2.7	<0.5	<0.5
1.0	1.5	–	–
2.0	1.3	–	–

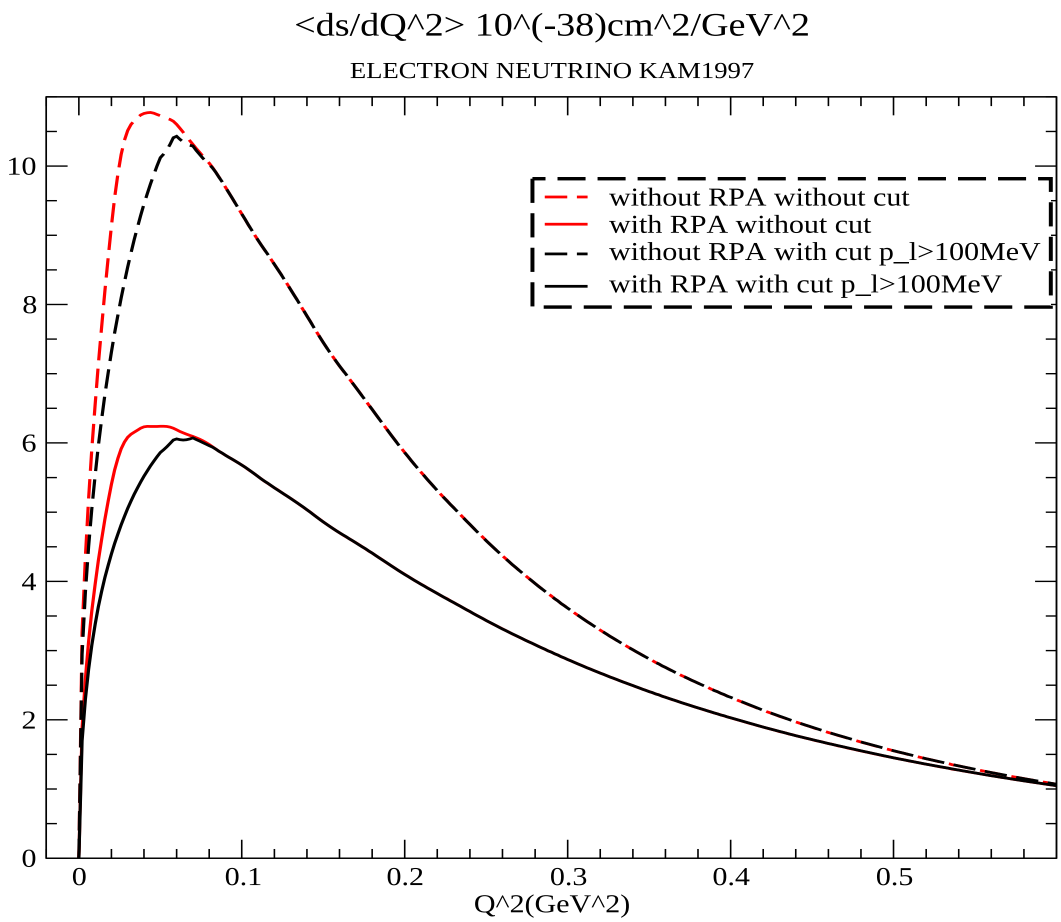
% reduction in σ as compared to Dipole



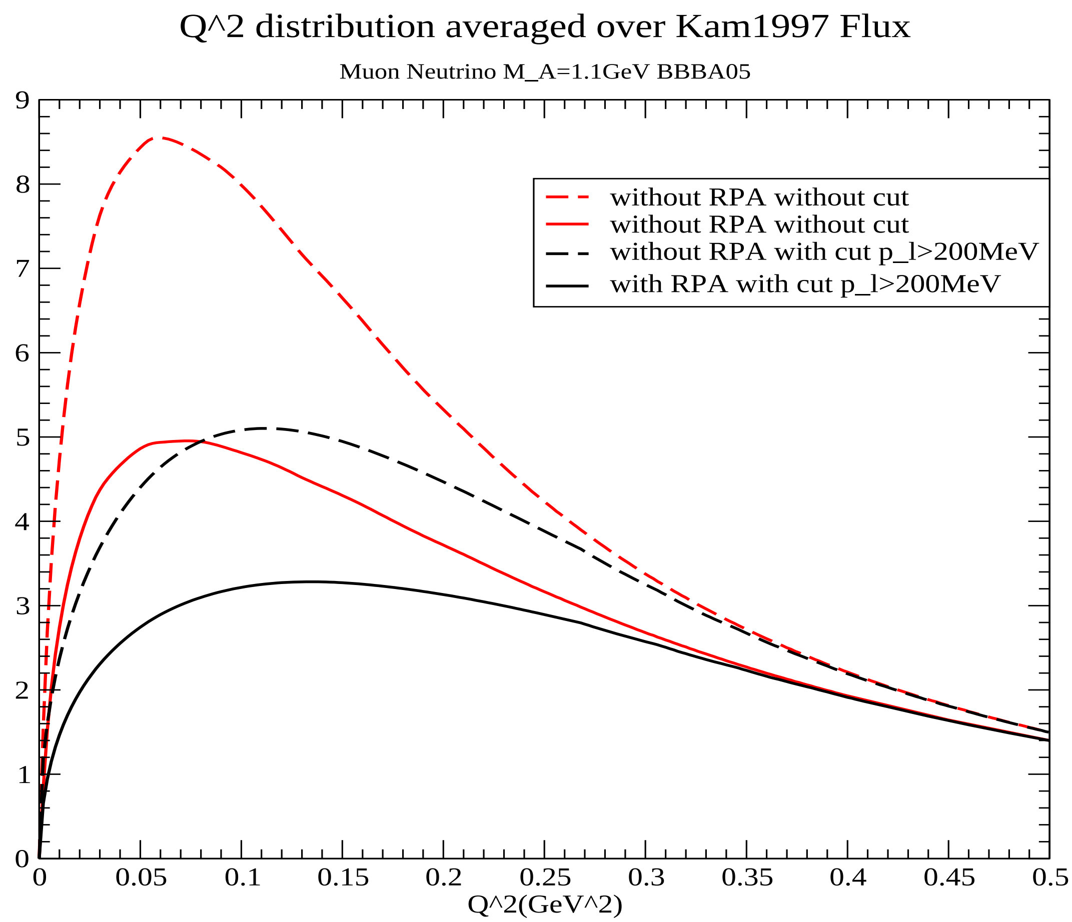
E(GeV)	M_A=1.05	M_A=1.21GeV
0.6	4.0	7.3
1.0	5.0	9.6
2.0	5.3	11.0
3.0	5.4	11.2

% change in σ as compared to M_A=1.1GeV

$< \frac{d\sigma}{dQ^2} >$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_e +^{16} O$ scattering averaged over Kamioka 1997 flux given by Honda et al.

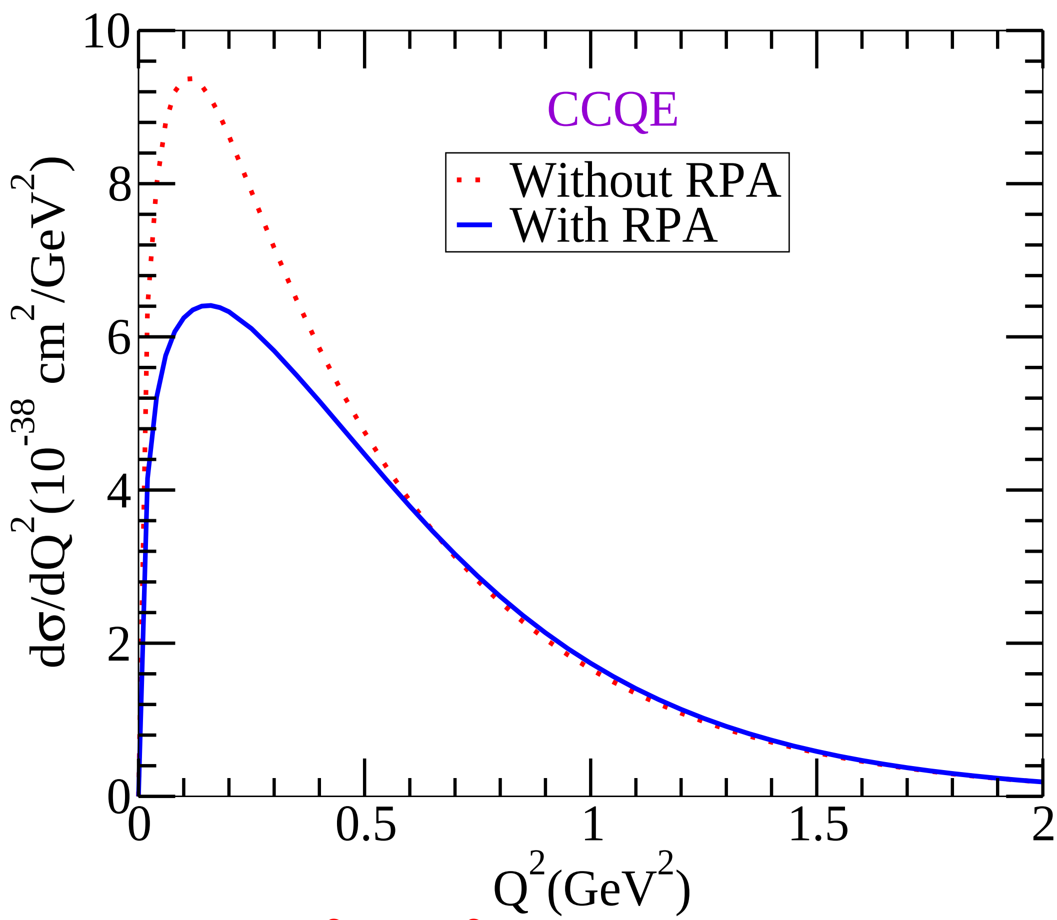


$< \frac{d\sigma}{dQ^2} >$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_\mu +^{16} O$ scattering averaged over Kamioka 1997 flux given by Honda et al.



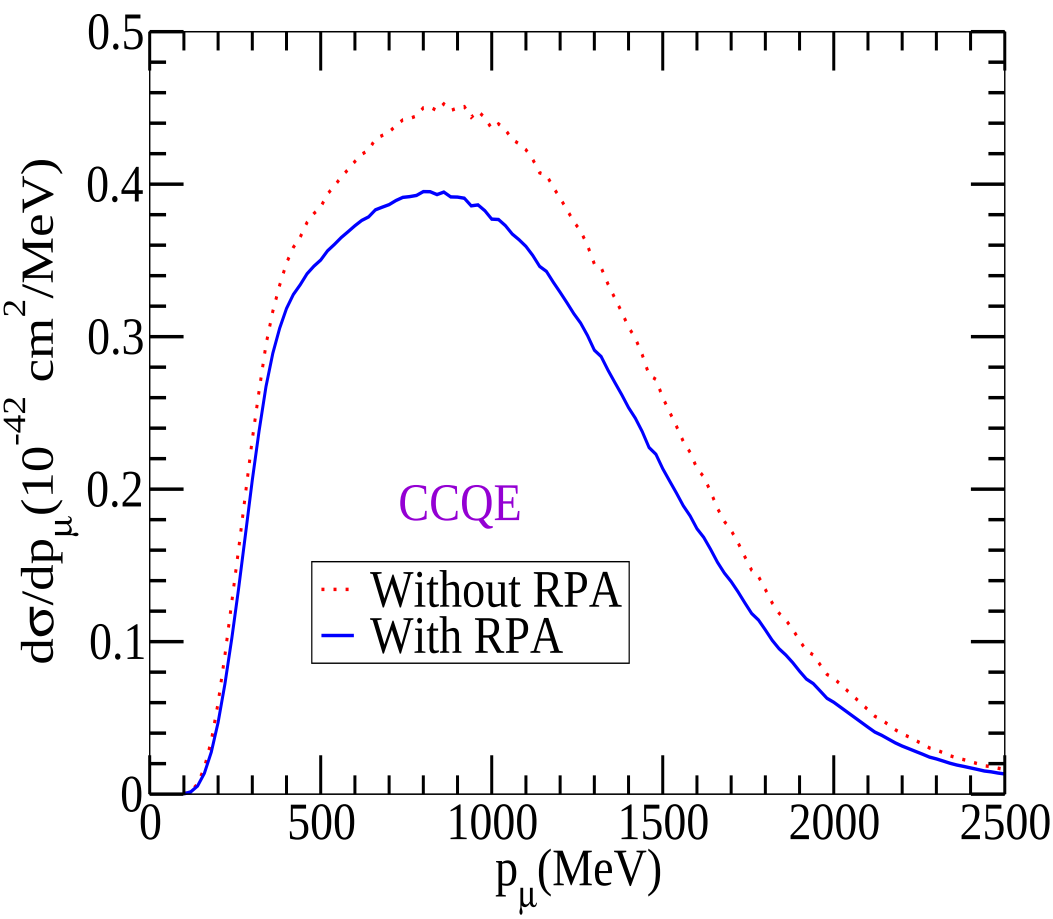
Q^2(GeV^2)	with RPA	with RPA with cut	Diff. with cut
0.02	42	35	40
0.2	30	30	15

$< \frac{d\sigma}{dQ^2} >$ vs Q^2 in $10^{-38}\frac{cm^2}{GeV^2}$ in $\nu_\mu +^{12} C$ scattering averaged over K2K flux



Q^2(GeV^2)	with RPA
0.02	35
0.12	32
0.2	25

$< \frac{d\sigma}{dp_l} >$ vs p_l in $10^{-40} \frac{cm^2}{MeV}$ in $\nu_\mu + ^{12}C$ scattering averaged over K2K flux



p_μ(MeV)	with RPA
860	12
980	14

Inelastic Scattering Cross Section

In the intermediate energy region of about 1GeV the pion production from nucleons is dominated by Δ excitation

$$\begin{aligned}
\nu_l(k) + p(p) &\rightarrow l^-(k') + \Delta^{++}(p') \\
&\qquad\qquad\qquad \searrow p + \pi^+ \\
\nu_l(k) + n(p) &\rightarrow l^-(k') + \Delta^{+}(p') \\
&\qquad\qquad\qquad \searrow n + \pi^+ \\
&\qquad\qquad\qquad \searrow p + \pi^0
\end{aligned}$$

In this model of Δ dominance the neutrino induced charged current one pion production is calculated using the Lagrangian

$$L = \frac{G_F}{\sqrt{2}}\, l_\mu(x)\ J^{\mu\dagger}(x) + h.c., \text{ where}$$

$$l_\mu(x) = \bar{\psi}(k')\ \gamma_\mu\ (1-\gamma_5)\ \psi(k)$$

$$J^\mu(x) = \cos\theta_c\ (\ V^\mu(x)\ +\ A^\mu(x)\ )$$

θ_c being the Cabibbo angle.

In the nucleus, the neutrino interacts with the nucleon moving inside the nucleus of density $\rho(r)$ with its corresponding momentum $\vec{p}$ constrained to be below its Fermi momentum.

The total scattering cross section is given by

$$\sigma = \frac{1}{(4\pi)^5}\int_{r_{min}}^{r_{max}}(Z\rho_p(r)+N\rho_n(r))d\vec{r}\int_{Q^2_{min}}^{Q^2_{max}}dQ^2\int_{-1}^{+1}d(cos\theta_{\pi q})\times \frac{\pi|\vec{k}'||\vec{k}_\pi|}{ME_\nu^2 E_l}\frac{1}{E'_p+E_\pi\left(1-\frac{|\vec{q}|}{|\vec{k}_\pi|}cos(\theta_\pi)\right)}|\mathcal{M}_{fi}|^2$$

The transition matrix element $\mathcal{M}_{fi}$ is given by

$$\mathrm{M}_{fi}=\frac{G_F a}{\sqrt{2}}\frac{f_{\pi N\Delta}}{m_\pi}\bar{\Psi}(\mathbf{P})k_\pi^\sigma\mathcal{P}_{\sigma\lambda}\mathcal{O}^{\lambda\alpha}L_\alpha u(\mathbf{p})$$

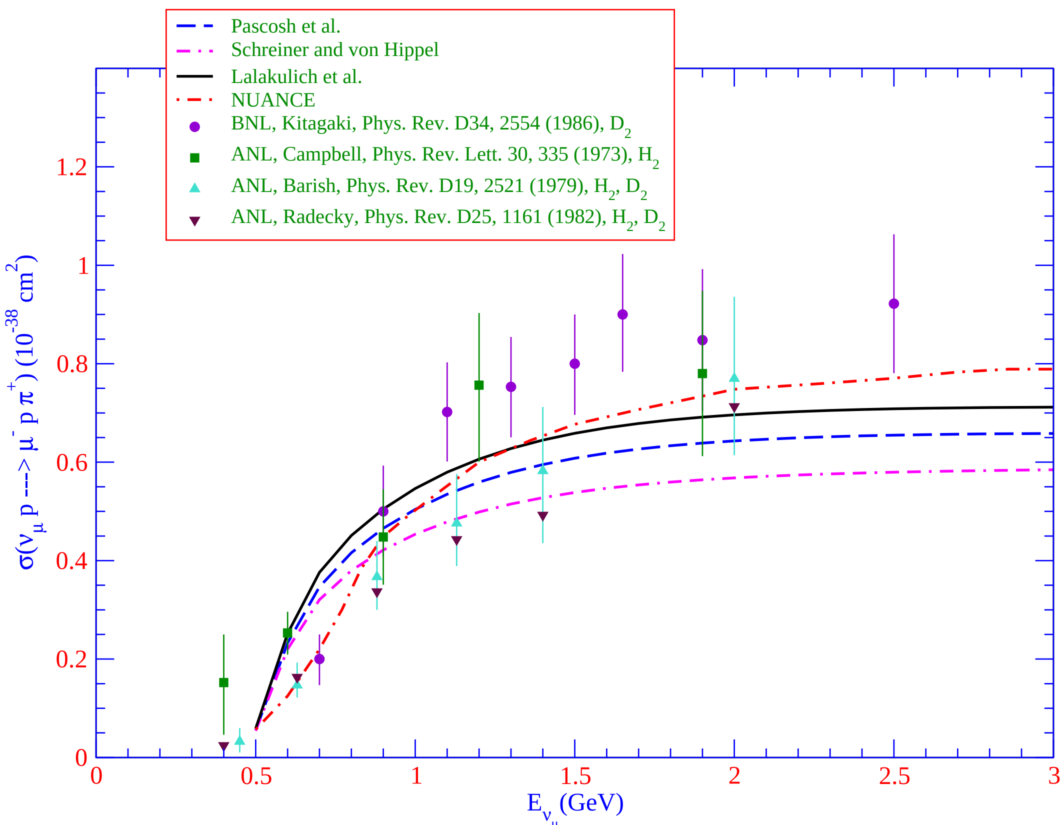
In nuclear medium the properties of Δ like its mass and decay width Γ are modified due to nuclear effects.

These are mainly due to following processes.

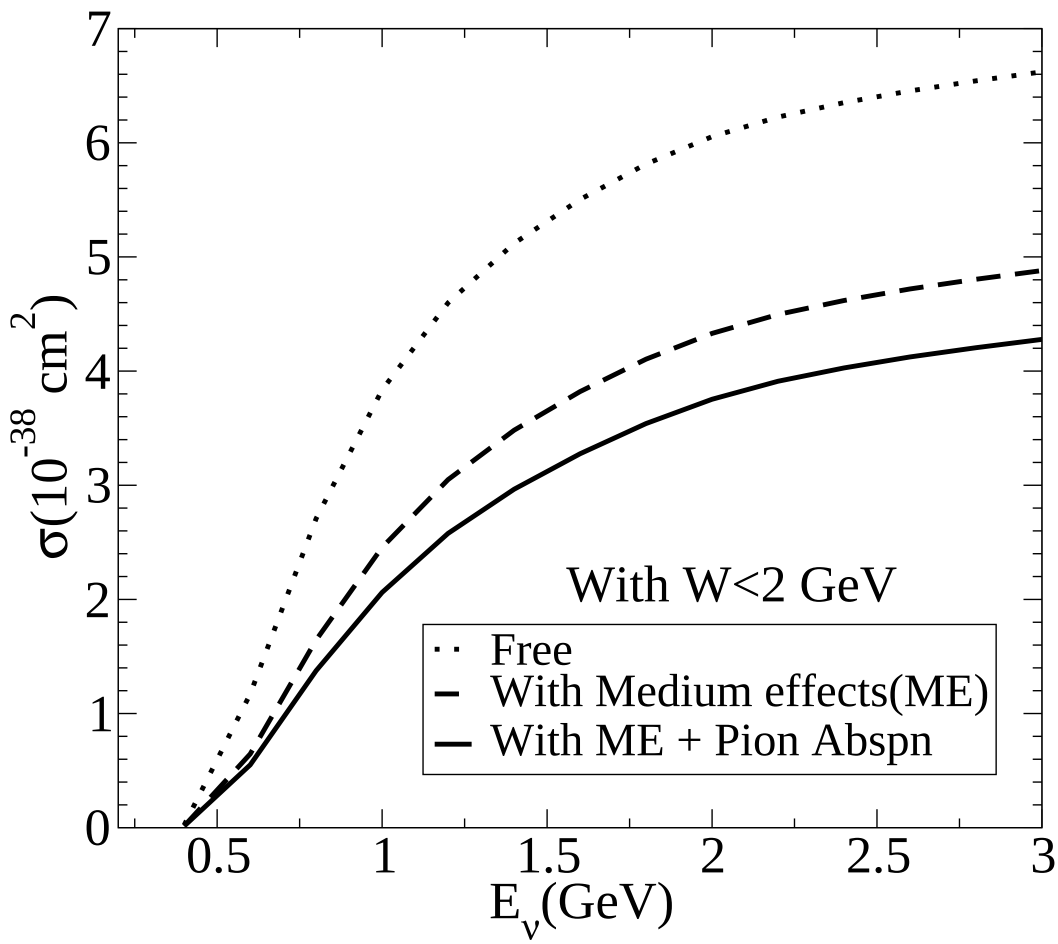
(i) In the nuclear medium Δs decay mainly through $\Delta \to N\pi$ channel. The final nucleons have to be above the Fermi momentum k_F of the nucleon in the nucleus thus inhibiting the decay. This leads to a modification in the delta decay width

$$\tilde{\Gamma} = \Gamma \times F(k_F, E_\Delta, k_\Delta)$$

(ii) In the nuclear medium there are additional decay channels open due to two body and three body absorption processes like $\Delta N \to NN$ and $\Delta NN \to NNN$ through which $\Delta's$ disappear in the nuclear medium without producing a pion while a two body Δ absorption process like $\Delta N \to \pi NN$ gives rise to some more pions. Due to these changes $\tilde{\Gamma}$ and M_Δ modify.

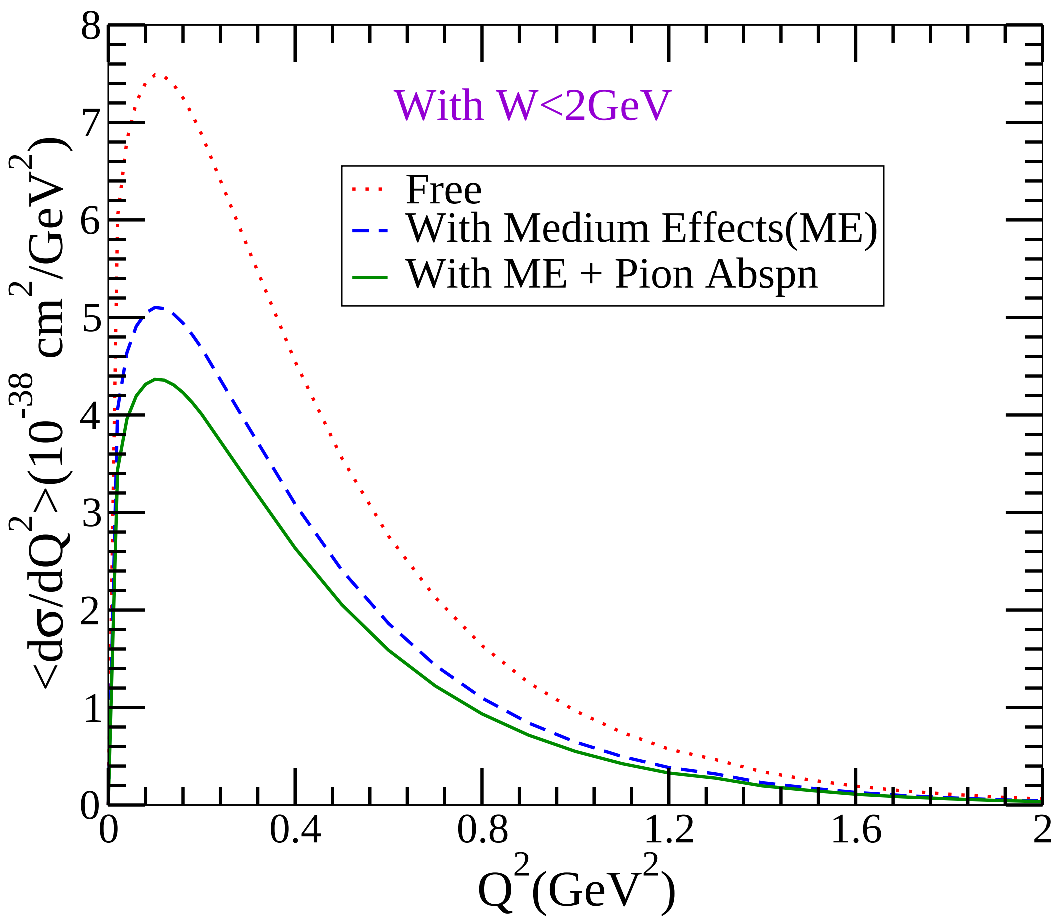


Pascosh et al.
Schreiner and von Hippel
Lalakulich et al.
NUANCE
BNL, Kitagaki, Phys. Rev. D34, 2554 (1986), D_2
ANL, Campbell, Phys. Rev. Lett. 30, 335 (1973), H_2
ANL, Barish, Phys. Rev. D19, 2521 (1979), H_2, D_2
ANL, Radecky, Phys. Rev. D25, 1161 (1982), H_2, D_2
$\sigma(\nu_\mu p \dashrightarrow \mu^- p \pi^+)$ (10^{-38} cm^2)
E_{ν_μ} (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2
2.5
3



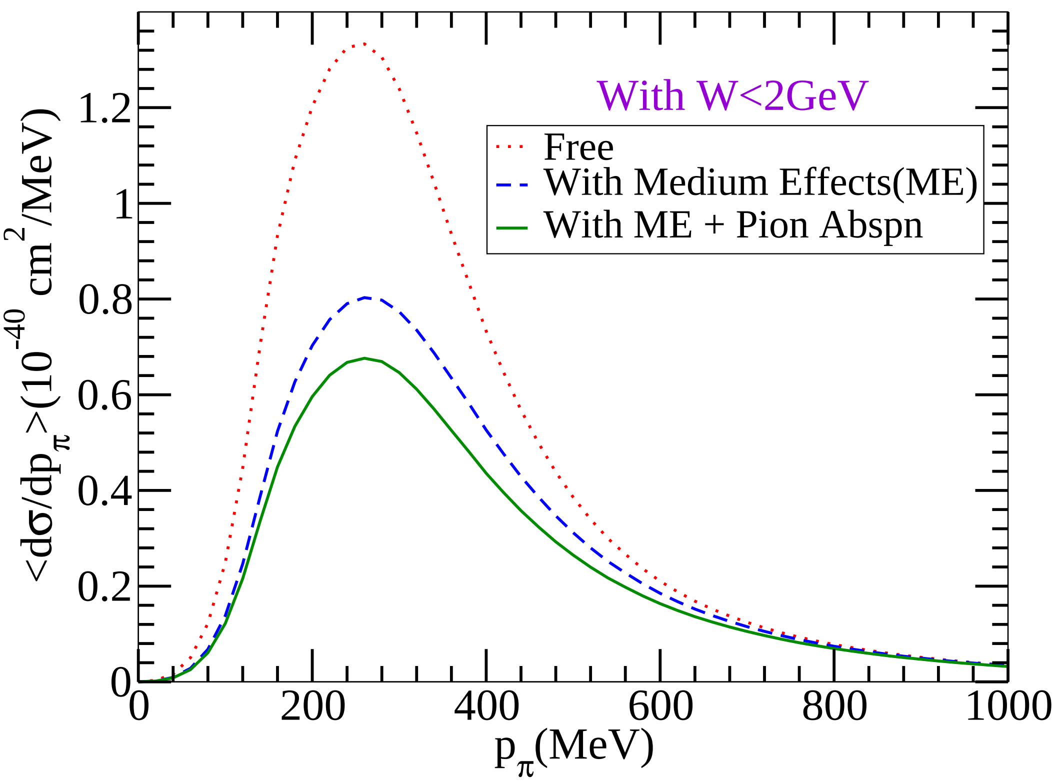
Total cross section for the charged current one π^+ process on ${}^{12}C$ target.

$E_\nu(MeV)$	without PA	with PA
800	40	16
1400	30	14
2000	28	13
3000	25	12



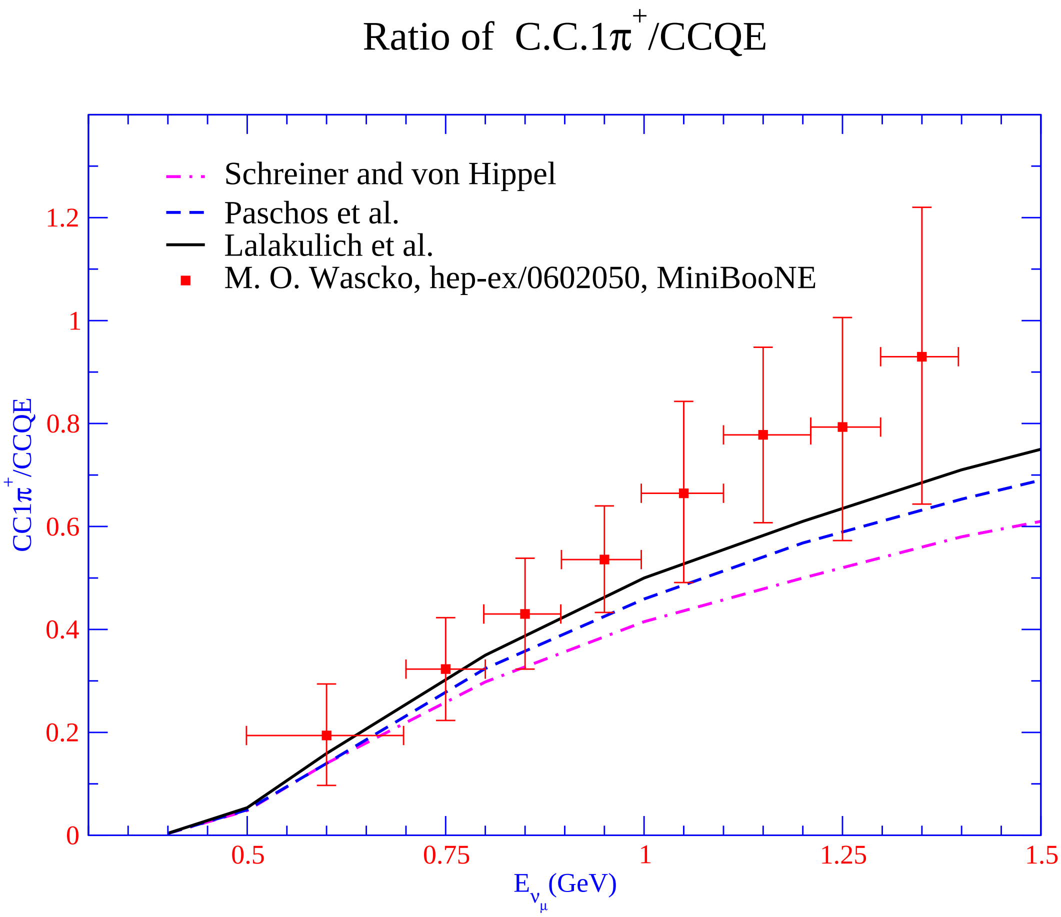
$< \frac{d\sigma}{dQ^2} >$ averaged over K2K spectrum for the charged current one π^+ process on ^{12}C target.

Q^2(GeV^2)	without PA	with PA
0.02	32	15
0.1	30	14



$< \frac{d\sigma}{dp_\pi} >$ averaged over K2K spectrum for the charged current one π^+ process on ^{12}C target.

dp_π(MeV)	without PA	with PA
200	40	15
300	36	16

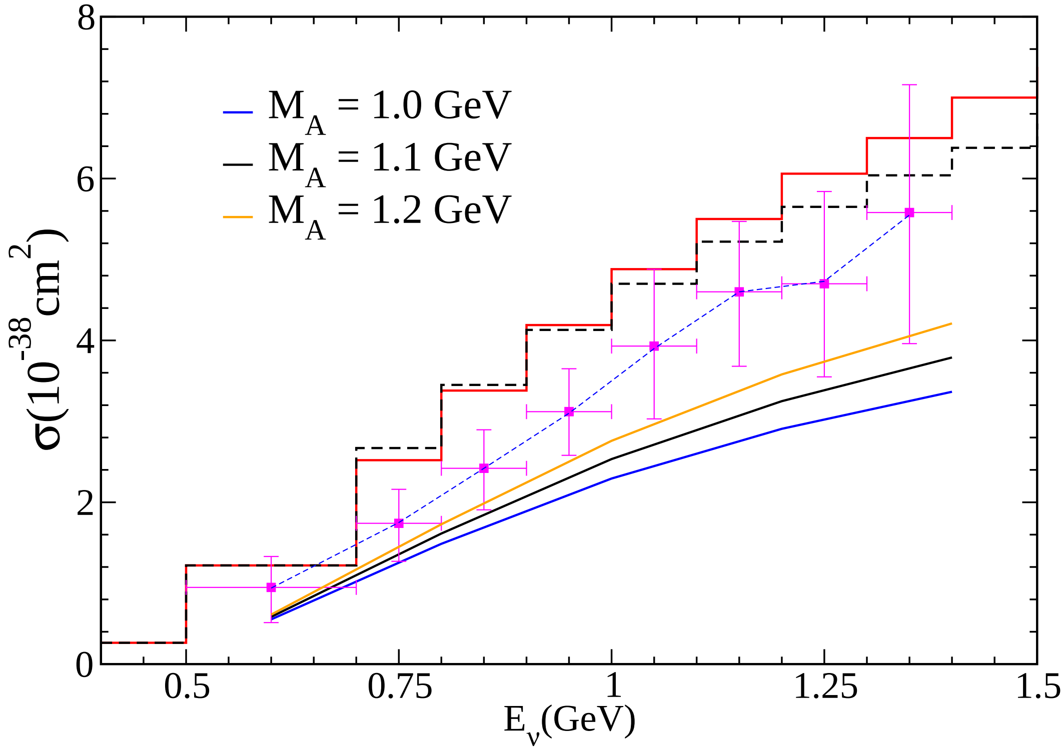


Ratio of C.C.1π+/CCQE
Schreiner and von Hippel
Paschos et al.
Lalakulich et al.
M. O. Wascko, hep-ex/0602050, MiniBooNE
CC1π+/CCQE
E_{ν_μ} (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
0.5
0.75
1
1.25
1.5

The experimental points are

$\sigma(\mathrm{CC1}\pi^+)=$

$[\frac{\sigma(CC1\pi^+)}{\sigma(CCQE)}]_{MiniBooNE} \times \sigma(\mathrm{CCQE})$ MC

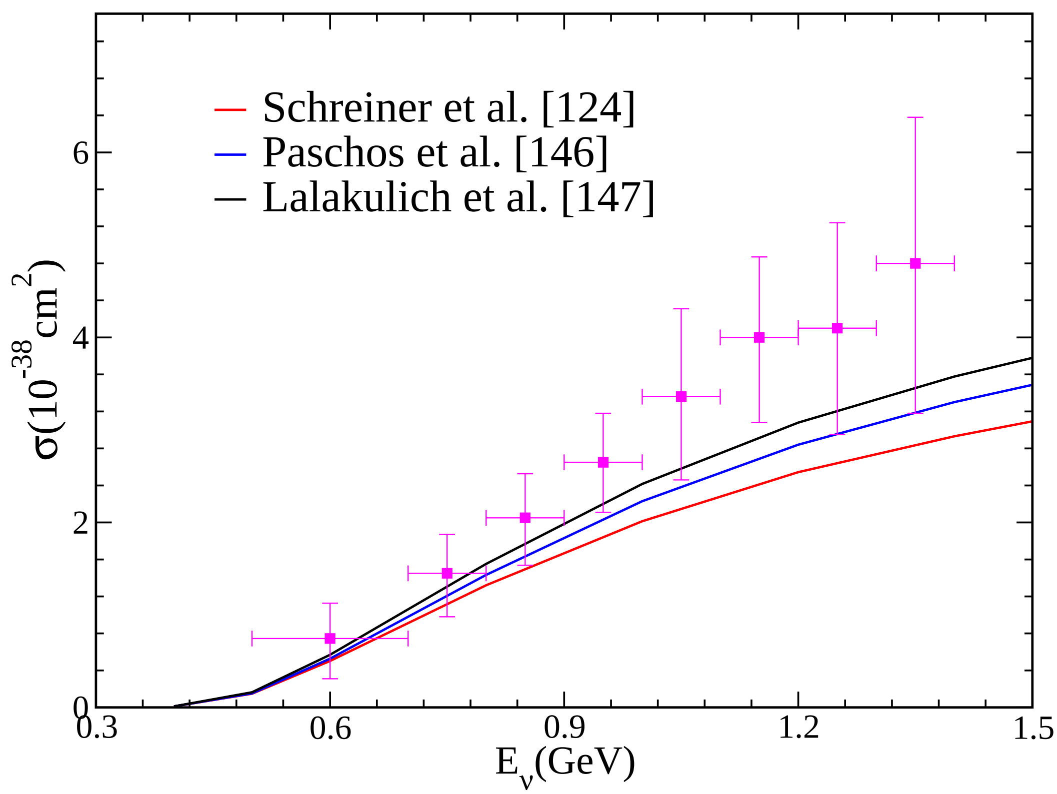


The dashed(solid) stairs are the cross sections from NEUGEN(NUANCE) MC generators. Experimental points are the MiniBooNE results. The theoretical curves show the $\mathrm{CC1}\pi^+$ cross section using Lalakulich et al. N-Δ transition form factors.

The dashed line is

$\sigma(\mathrm{CC1}\pi^+)=$

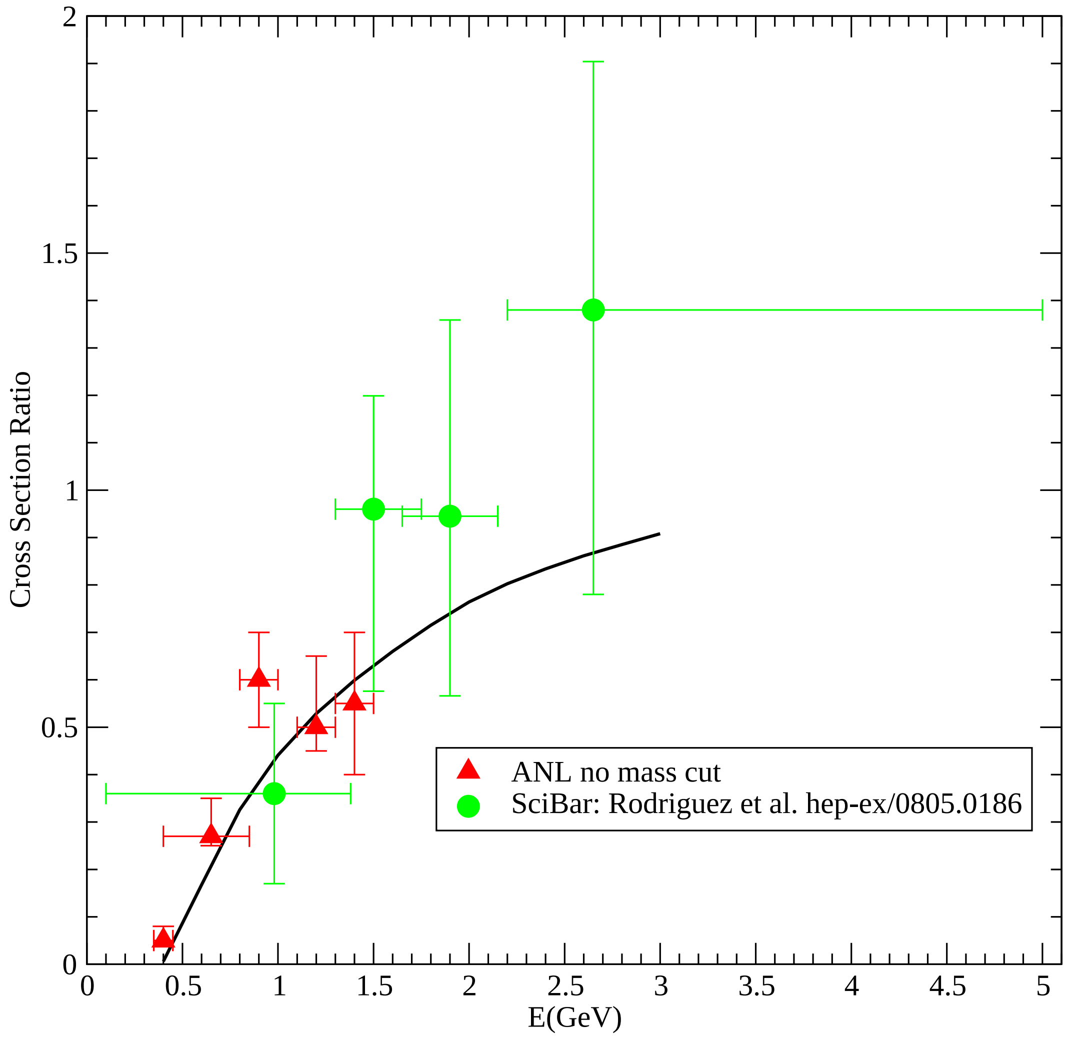
$[\frac{\sigma(CC1\pi^+)}{\sigma(CCQE)}]_{MiniBooNE} \times \sigma(\mathrm{CCQE})$ without RPA with M_A=1.05GeV



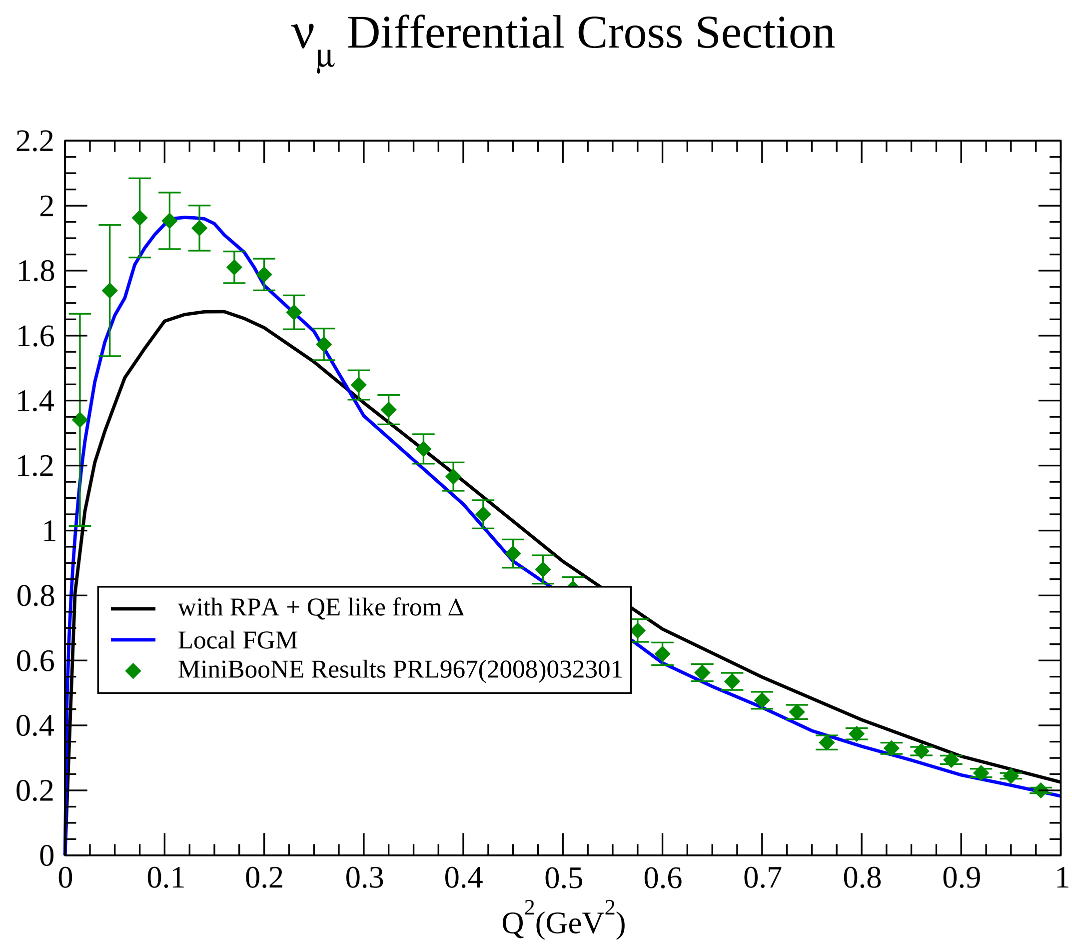
$CC1\pi^+$ cross section for ν_μ induced reaction in ^{12}C.

The experimental points show
$\sigma(CC1\pi^+)=$
$[\frac{\sigma(CC1\pi^+)}{\sigma(CCQE)}]_{MiniBooNE} \times \sigma(CCQE)$ with RPA
with M_A=1.05GeV

$\frac{\sigma_{CC1\pi^+}}{\sigma_{CCQE}}$ for ν_μ induced reaction in Polystyrene (C_8H_8).

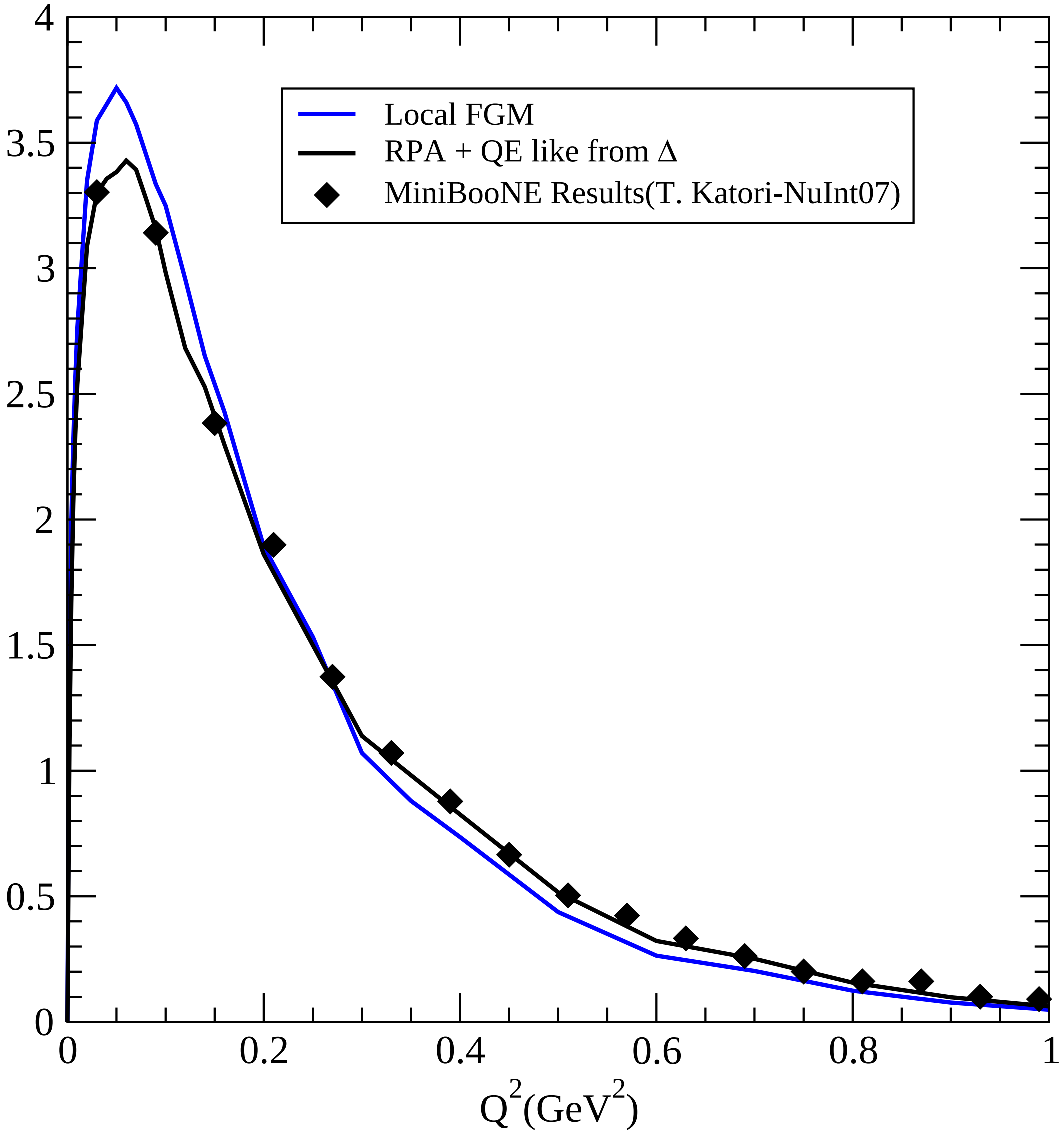


Results from the K2K Collabn. for $\frac{CC1\pi^+}{CCQE}$



νμ Differential Cross Section
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Q2(GeV2)
with RPA + QE like from Δ
Local FGM
MiniBooNE Results PRL967(2008)032301

Antineutrino Differential Cross Section



T. Katori, AIP Conf. Proc. 967 (2007) 123.

Coherent Weak Pion Production

The coherent pion production is the process in which the nucleus remains in the ground state. We calculate the coherent pion production induced by charged current interaction i.e.

$$\nu + {}^A_Z X \rightarrow l^- + \pi^+ + {}^A_Z X$$

The calculations are done in a local density approximation using Δ dominance:

Matrix Element

$$\mathcal{A} = \frac{G_F}{\sqrt{2}} \quad \left[\bar{u}(k')\ \gamma^\mu\ (1-\gamma_5)\ u(k)\right] \\ \times \left[\left(J^\mu_s + J^\mu_u\right)\ F(\mathbf{q}-\mathbf{p}_\pi)\right]$$

$$J_s^{\mu} = \sqrt{3}\frac{G_F}{\sqrt{2}} \cos\theta_C \frac{f_{\pi N\Delta}}{m_\pi} p_\sigma^\pi \sum_s \bar{\Psi}^s(p')\Delta^{\sigma\lambda} O_{\lambda\mu} \Psi^s(p)$$

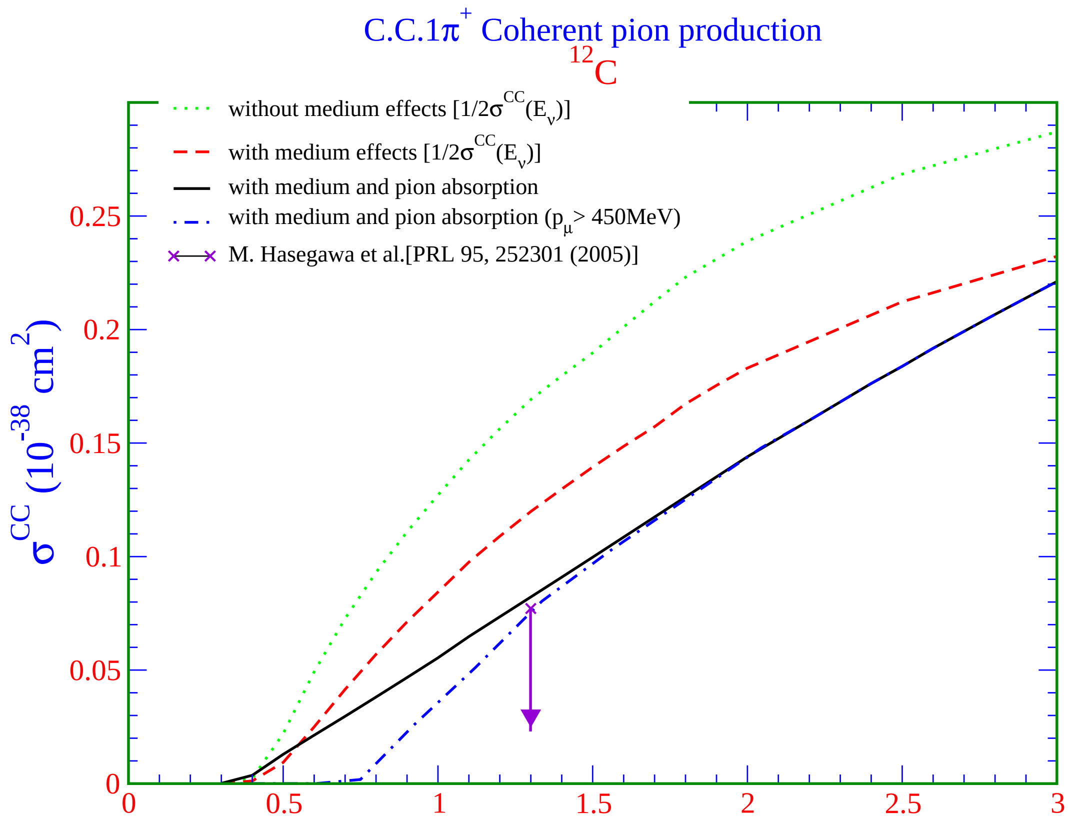
$$J_u^{\mu} = \sqrt{3}\frac{G_F}{\sqrt{2}} \cos\theta_C \frac{f_{\pi N\Delta}}{m_\pi} \sum_s \bar{\Psi}^s(p') p_\sigma^\pi O^{\sigma\lambda} \Delta_{\lambda\mu} \Psi^s(p)$$

$$F(\mathbf{q}-\mathbf{p}_\pi) = \int d^3r \left[\rho_p(\mathbf{r}) + \frac{1}{3}\rho_n(\mathbf{r})\right] e^{i(\mathbf{q}-\mathbf{p}_\pi).\mathbf{r}}$$

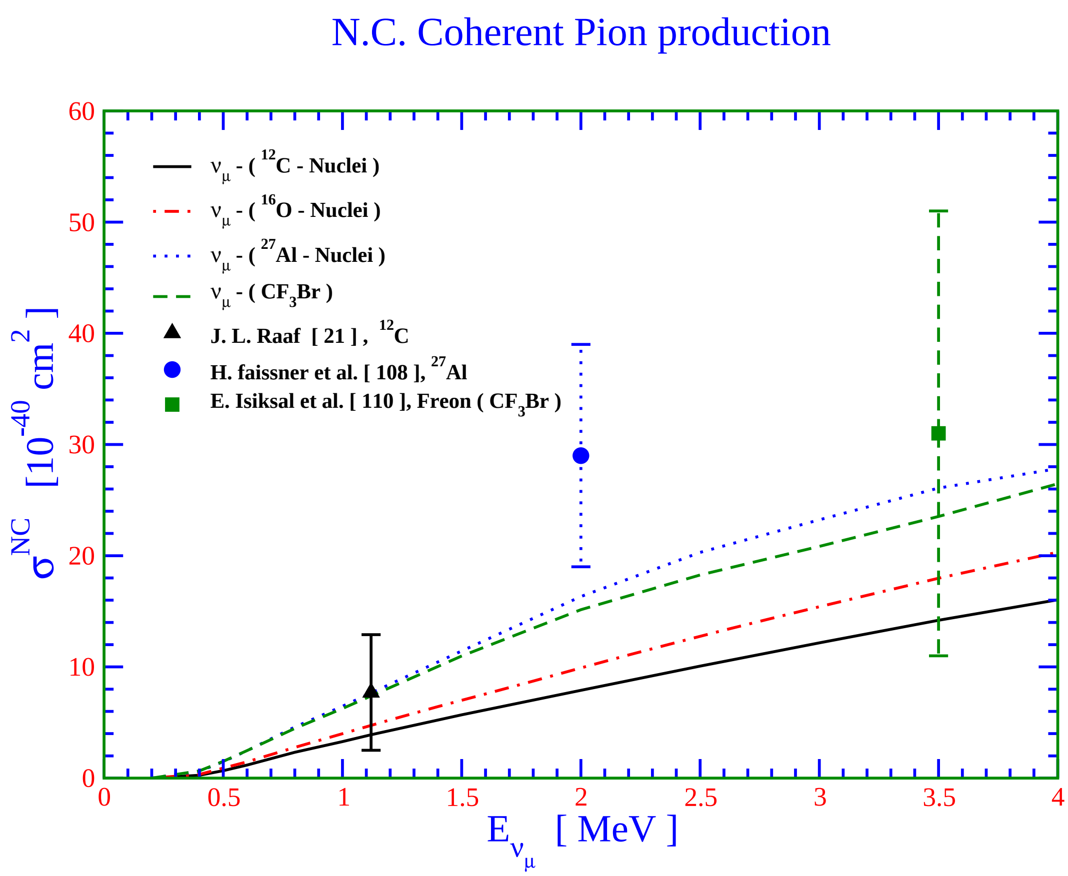
Using these expressions the following form of the double differential cross section for pion production is obtained

$$\left[\frac{d^5\sigma}{dE_\pi d\Omega_\pi d\Omega_{ll'}}\right]_{CC} = \frac{1}{8}\frac{1}{(2\pi)^5}\frac{M}{E_l}|\ \mathbf{k}'|\ |\ \mathbf{k}_\pi|\ \frac{1}{\mathcal{R}} \bar{\sum}\sum |\mathcal{A}|^2$$

$$\mathcal{R} \ = \ \left[(E_{p'} + E_{l'} - E_l \cos\theta_{ll'}) - \frac{|\mathbf{k}_\pi|}{|\mathbf{q}|}(E_{l'} - E_l \cos\theta_{ll'}) \cos\theta_{\pi q}\right]$$



C.C.1π+ Coherent pion production
12C
without medium effects [1/2σCC(Eν)]
with medium effects [1/2σCC(Eν)]
with medium and pion absorption
with medium and pion absorption (pμ> 450MeV)
M. Hasegawa et al.[PRL 95, 252301 (2005)]
σCC (10-38 cm2)
0
0.05
0.1
0.15
0.2
0.25
0
0.5
1
1.5
2
2.5
3



N.C. Coherent Pion production
νμ - (12C - Nuclei)
νμ - (16O - Nuclei)
νμ - (27Al - Nuclei)
νμ - (CF3Br)
J. L. Raaf [21] , 12C
H. faissner et al. [108], 27Al
E. Isiksal et al. [110], Freon (CF3Br)
σNC [10-40 cm2]
0
10
20
30
40
50
60
0
0.5
1
1.5
2
2.5
3
3.5
4
Eνμ [MeV]

Deep Inelastic Charged Current Neutrino Nucleus Reaction

The differential cross section for the reaction

$$\nu_l(\bar{\nu}_l) + N \to l^-(l^+) + X,$$

in the rest frame of the nucleon is expressed as,

$$\frac{d^2\sigma_{\nu,\bar{\nu}}^N}{d\Omega' dE'} = \frac{{G_F}^2}{(2\pi)^2}\,\frac{|\mathbf{k}'|}{|\mathbf{k}|}\,\left(\frac{m_W^2}{q^2-m_W^2}\right)^2 L_{\nu,\bar{\nu}}^{\alpha\beta}\, W_{\alpha\beta}^N\,,$$

Lepton tensor for antineutrino(neutrino) scattering $L^{\alpha\beta}$ is given by

$$\mathsf{L}^{\alpha\beta} = k^\alpha k'^\beta + k^\beta k'^\alpha - k.k' g^{\alpha\beta} \pm i\epsilon^{\alpha\beta\rho\sigma} k_\rho k'_\sigma\,,$$

$$W_{\alpha\beta}^N = \frac{1}{2\pi}\bar{\sum_{s_N}}\sum_X \sum_{s_i} \prod_{i=1}^n \int \frac{d^3p'_i}{(2\pi)^3} \prod_{l\epsilon f}\left(\frac{2M'_l}{2E'_l}\right)\prod_{j\epsilon b}\left(\frac{1}{2\omega'_j}\right)$$

$$\langle X|J_\alpha|N\rangle\langle X|J_\beta|N\rangle^*(2\pi)^4\delta^4(p+q-\sum_{i=1}^n p'_i)\,,$$

Nuclear effects in neutrino scattering

There are two main nuclear effects:

I. A kinematic effect which arises as the struck nucleon is not at rest but is moving with a Fermi momentum in the rest frame of the nucleus, leading to a Lorentz contraction of the incident flux.

II. The dynamic effects which arise due to Fermi motion, Pauli blocking and strong interaction of the initial nucleon in the nuclear medium.

The expression for the cross section in nuclear medium:

$$\frac{d^2\sigma^A_{\nu,\bar{\nu}}}{d\Omega' dE'} = \frac{G_F^2}{(2\pi)^2}\,\frac{|\mathbf{k}'|}{|\mathbf{k}|}\,\left(\frac{m_W^2}{q^2-m_W^2}\right)^2 L^{\alpha\beta}_{\nu,\bar{\nu}}\,W^A_{\alpha\beta}$$

$W^A_{\alpha\beta}$: nuclear hadronic tensor defined in terms of nuclear hadronic structure functions $W_{iA}(x,Q^2)$

Theoretical Spectral Function is used to describe the momentum distribution of nucleons in the nucleus.

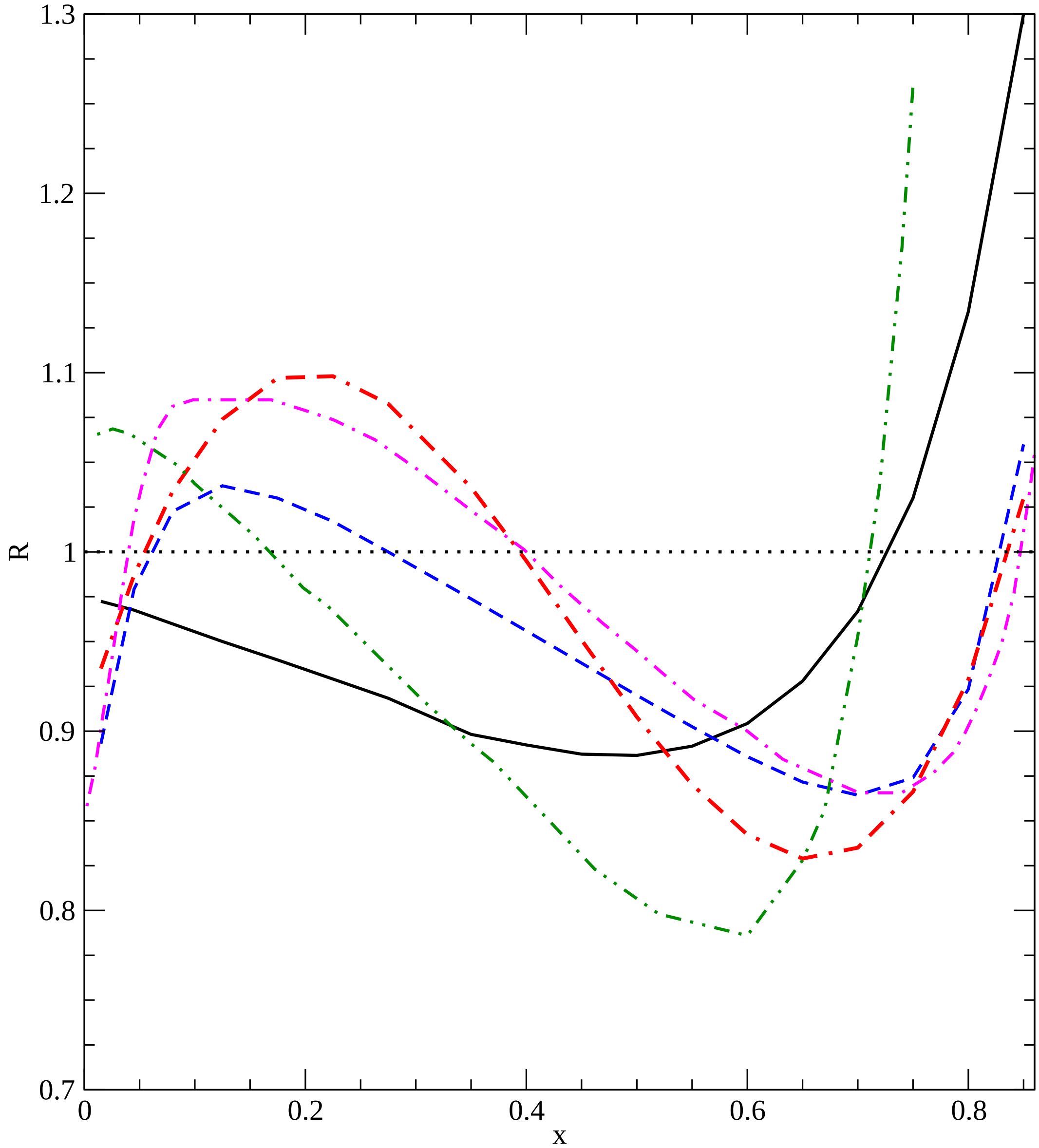
Spectral Function is calculated using the Lehmann's repsn. for the rel. nucleon prop.

Nuclear Many Body theory is used to calculate it for an interacting Fermi sea.

We use the local density approximation to translate the theoretical formulation from infinite nuclear matter calculation to finite nucleus.

$$F_3^A(x, Q^2) = 4 \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(p)}$$

$$\int_{-\infty}^{\mu} dp^0 S_h(p^0, p, \rho(r)) \left(\frac{p_0\gamma - p_z}{(p_0 - p_z\gamma)\gamma} \right) F_3^N(x_N, Q^2)$$



Results for the ratio $R = \frac{F_3^A(x)}{AF_3^N(x)}$ at $Q^2 = 5$ GeV^2.

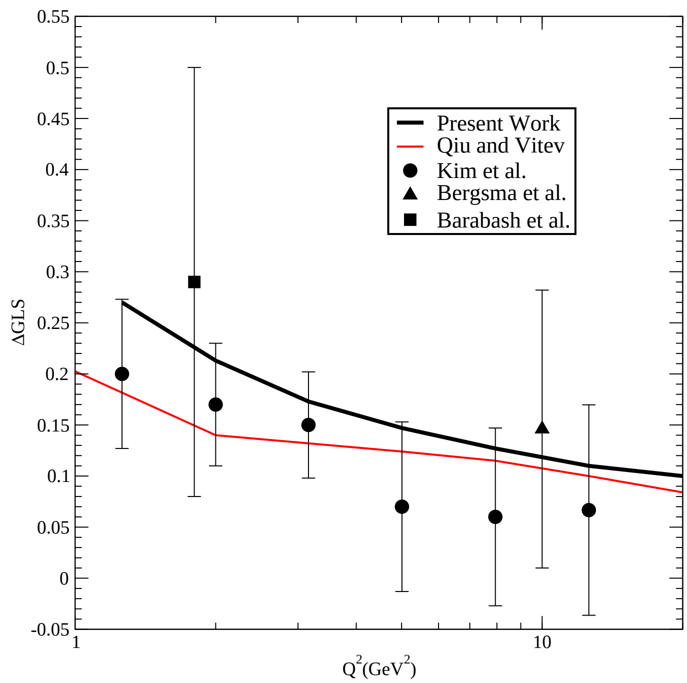
solid line: our work using MRST2004 NNLO PDF;

double dashed-dotted line: Hirai et al.,PR C 70, 044905(2004).

short dashed line: NuTeV collabn., PR D 74, 012008(2006).

dashed-double dotted: Kulagin, NP A 640, 435(1998).

dashed-dotted line: Kulagin and Petti, PR D 76, 094033(2007)



ΔGLS=$\frac{1}{3}(3-\int_0^1 F_3^A(x,Q^2)dx)$ vs Q^2.

J. H. Kim et al.(CCFR Collabn.),PRL 81 (1998) 3595.

F. Bergsma et al.(CHARM Collabn.), PLB 123 (1988) 269.

L. S. Barabash et al.(IHEP-JINR Collabn.), arXiv:9611.012[hep-ex].

Conclusions

Summary of NME

A. Quasielastic Scattering

1. NME reduces the total cross section due to RPA (20-30%) for ν and $\bar{\nu}$.

2. NME increases σ due to quasielastic-like effects through ΔN $\rightarrow$ NN (10-15%).

3. NME improves the agreement with MiniBooNE results of $< \frac{d\sigma}{dQ^2} >$ for $\bar{\nu}$.

4. NME worsens the agreement with MiniBooNE results of $< \frac{d\sigma}{dQ^2} >$ for ν.

B. One Pion Production

1. NME reduces the total cross section for ν and $\bar{\nu}$ (20-25%).

2. NME does not affect Q^2 dependence so Q^2 disagreement with MiniBooNE results remains.

C. Deep Inelastic Scattering

1. NME on $F_3(x, Q^2)$ leads to reduction at large Q^2. Compared to Kulagin results the reduction is smaller and Q^2 dependence is different.

2. NME results on $F_3(x, Q^2)$ are in qualitative agreement with phenomenological analysis of NuTeV collaboration but not with Hirai et al.

3. NME lead to better agreement with NuTeV and CCFR results.