(Anti) Neutrino Induced Single Pion Production From Nuclei

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Single Pion Production through Excitation of Baryon Resonances and their subsequent decays

Incoherent Pion Production

$$\nu_l(k) + {}^A_Z X(p) \rightarrow l^-(k') + \pi^\alpha(k_\pi) + \ldots\ldots\ldots$$

Coherent Pion Production

$$\nu_l(k) + {}^A_Z X(p) \rightarrow l^-(k') + \pi^+(k_\pi) + {}^A_Z X(p')$$

Energy Region Of Interest

$E_{\nu} < 3$ GeV

At:

K2K

MiniBooNE

β-beam

Atmospheric

MINERνA

Neutrino Event Generators

NUANCE, NEUGEN, NEUT, NUX, GENEVE, FLUKA etc.

All the neutrino event generators use some Nuclear Model to estimate σ but inclusion of nuclear effects is mainly limited to Quasielastic reactions

Common theoretical inputs to all neutrino event generators

- **Llewellyn Smith free nucleon Q.E. X-section**
  Phys. Rep. 3C, 261 (1972).
- **Rein and Sehgal Resonance X-section**
  Ann. Phys. 133, 79 (1981).
- **Standard DIS formula for high Q^2**

Inputs which are different for various neutrino event generators

- **Treatment of Nuclear Effects**
- **Joining of resonance and DIS**
- **Treatment of DIS**

- Resonance Processes

  ✓Rein and Sehgal model is used [Ann. Phys. 133, 79 (1981)].

  ✓Treatment of Nuclear medium effects is not complete

An ad hoc suppression of pion production:

  ✓20% for $I_3 = \pm 1/2$ Resonance excitations

  ✓10% for $I_3 = \pm 3/2$ Resonance excitations

  D.Casper, NPB(PS) 112, 161 (2002)

- Coherent Process

  ✓Rein and Sehgal model is used [Ann. Phys. 133, 79 (1981)].

- Deep Inelastic Scattering

  ✓Parton Distribution function of Albright and Jarlskog

  ✓Nuclear medium Effects (by Bodek and Yang)

Weak Pion Production From Nucleons

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

Charged Current Single Pion production On Free Nucleon

$$\nu_l p \to l^- \Delta^{++} \Rightarrow l^- p \pi^+ \qquad \bar{\nu}_l p \to l^+ \Delta^+ \Rightarrow l^+ p \pi^0$$

$$\nu_l n \to l^- \Delta^+ \Rightarrow l^- n \pi^+ \qquad \bar{\nu}_l p \to l^+ \Delta^+ \Rightarrow l^+ n \pi^+$$

$$\nu_l n \to l^- \Delta^+ \Rightarrow l^- p \pi^0 \qquad \bar{\nu}_l n \to l^+ \Delta^- \Rightarrow l^+ n \pi^-$$

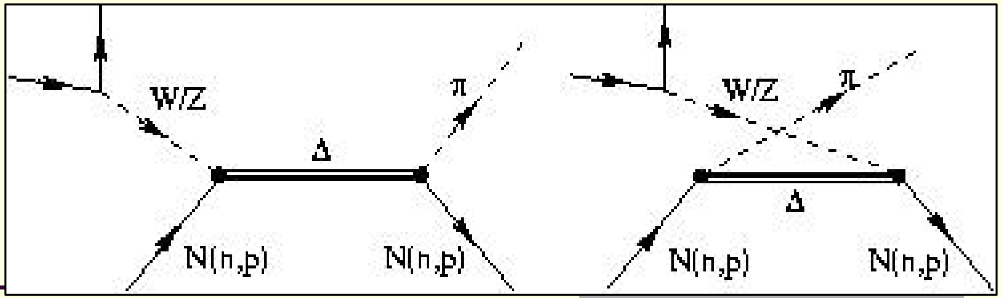
Neutral Current Single Pion production On Free Nucleon

$$\nu_l p \to \nu_l \Delta^+ \Rightarrow \nu_l p \pi^0 \qquad \bar{\nu}_l p \to \bar{\nu}_l \Delta^+ \Rightarrow \bar{\nu}_l p \pi^0$$

$$\nu_l p \to \nu_l \Delta^+ \Rightarrow \nu_l n \pi^+ \qquad \bar{\nu}_l p \to \bar{\nu}_l \Delta^+ \Rightarrow \bar{\nu}_l n \pi^+$$

$$\nu_l n \to \nu_l \Delta^0 \Rightarrow \nu_l n \pi^0 \qquad \bar{\nu}_l n \to \bar{\nu}_l \Delta^0 \Rightarrow \bar{\nu}_l n \pi^0$$

$$\nu_l n \to \nu_l \Delta^0 \Rightarrow \nu_l p \pi^- \qquad \bar{\nu}_l n \to \bar{\nu}_l \Delta^0 \Rightarrow \bar{\nu}_l p \pi^-$$



In the model of Δ dominance the neutrino induced Charged Current one pion production is calculated using the basic Weak interaction Lagrangian

$$L_{\text{int}}^{weak} = -\frac{g}{2\sqrt{2}} J_{CC}^{\mu}(x) W_{\mu}^{\dagger}(x) + h.c.$$

Weak Charged current coupled to W_μ field

$$J_{CC}^{\mu}(x) = l_{lep}^{\mu}(x) + J_{had}^{\mu}(x)$$

Leptonic Weak Current

$$l_{lep}^{\mu}(x) = \overline{\psi}_l(k')\gamma^{\mu}(1-\gamma^5)\psi_{\nu_l}(k)$$

Hadronic Weak Current

$$J_{had}^{\mu}(x) = Cos\theta_c(J_{\mu}^{V}(x) + J_{\mu}^{A}(x))$$

The Matrix Element For Δ Production

$$\nu_l(k) + p(p) \rightarrow l^-(k') + \Delta^{++}(P)$$

$$\nu_l(k) + n(p) \rightarrow l^-(k') + \Delta^{+}(P)$$

$$\langle l^- \Delta^{++} | M | \nu_l \, p \rangle = \frac{G}{\sqrt{2}} Cos\,\theta_c \, l_\mu^{lep} \langle \Delta^{++} | V^\mu - A^\mu | p \rangle$$

$$\langle \Delta^{++} | V^\mu | p \rangle = \sqrt{3}\,\overline{\psi}_\alpha(P) \left[\left(\begin{array}{l} \frac{C_3^V(q^2)}{M}(g^{\alpha\mu}\not{q} - q^\alpha \gamma^\mu) + \frac{C_4^V(q^2)}{M^2}(g^{\alpha\mu} q\cdot P - q^\alpha P^\mu) \\ + \frac{C_5^V(q^2)}{M^2}(g^{\alpha\mu} q\cdot p - q^\alpha p^\mu) + \frac{C_6^V(q^2)}{M^2}(q^\alpha q^\mu) \end{array} \right) \gamma^5 \right] u(p)$$

$$\langle \Delta^{++} | A^\mu | p \rangle = \sqrt{3}\,\overline{\psi}_\alpha(P) \left[\left(\begin{array}{l} \frac{C_3^A(q^2)}{M}(g^{\alpha\mu}\not{q} - q^\alpha \gamma^\mu) + \frac{C_4^A(q^2)}{M^2}(g^{\alpha\mu} q\cdot P - q^\alpha P^\mu) \\ + C_5^A(q^2) g^{\alpha\mu} + \frac{C_6^A(q^2)}{M^2}(q^\alpha q^\mu) \end{array} \right) \right] u(p)$$

$C_i^V(q^2)(i=3-6)$ Weak Vector N-Δ Transition From Factors

$C_i^A(q^2)(i=3-6)$ Weak Axial Vector N-Δ Transition From Factors

N-Δ Transition Form Factors

Vector Form Factors

They are generally parameterized in Dipole form:

$$C_i^V(q^2) = C_i^V(0)\left(1 - \frac{q^2}{M_V^2}\right)^{-2} \qquad \text{For i = 3,4,5}$$

However, some authors have recently proposed modified Dipole Form factors. For example, Lalakulich et al., PRD 74, 014009 (2006):

$$C_i^V(q^2) = C_i^V(0)\left(1 - \frac{q^2}{M_V^2}\right)^{-2} D_i$$

$$D_i = \left(1 - \frac{q^2}{4M_V^2}\right)^{-1} \qquad \text{For i = 3,4}$$

$$D_i = \left(1 - \frac{q^2}{0.776 M_V^2}\right)^{-1} \qquad \text{For i = 5}$$

Paschos et al., PRD 69, 014013 (2004) and Leitner et al., PRC 73, 065502 (2006) use:

$$C_3^V(q^2) = C_3^V(0)\left(1 - \frac{q^2}{M_V^2}\right)^{-2}\left(1 - \frac{q^2}{4M_V^2}\right)^{-1} \qquad W = \sqrt{(p+q)^2}$$

Axial Vector Form Factors

The Axial Vector form factors are generally parameterized in a Modified Dipole form and are given as:

$$C_i^A(q^2) = C_i^A(0)\left(1 - \frac{q^2}{M_A^2}\right)^{-2} D_i$$

$$D_i = 1 - \frac{a_i q^2}{(b_i - q^2)} \qquad i = 3,4,5$$

Schreiner and F. von Hippel NPB 58, 333 (1973) and Singh et al. PLB 416, 23 (1998)

$a_3 = b_3 = 0$,

$a_4 = a_5 = -1.21$,

$b_4 = b_5 = 2\text{GeV}^2$

Lalakulich et al., PRD 74, 014009 (2006)

Paschos et al., PRD 69, 014013 (2004)

Leitner et al., PRC 73, 065502 (2006)

$$C_i^A(q^2) = C_i^A(0)\left(1 - \frac{q^2}{M_A^2}\right)^{-2} D_i$$

$$D_i = \left(1 - \frac{q^2}{3M_A^2}\right)^{-1} \qquad i = 3,4,5$$

References	$C_3^V(0)$	$C_4^V(0)$	$C_5^V(0)$	$C_3^A(0)$	$C_4^A(0)$	$C_5^A(0)$	M_V(GeV)	M_A(GeV)
Schreiner and F. von Hippel	2.05	$-M/M_\Delta$	0.0	0.0	-0.30	1.2	0.73	1.05
Singh et al.	2.05	$-M/M_\Delta$	0.0	0.0	-0.30	1.2	0.73	1.05
Paschos et al.	1.95	-M/W	0.0	0.0	-0.25	1.2	0.84	1.05
Lalakulich et al.	2.13	-1.51	0.48	0.0	-0.25	1.2	0.84	1.05
Leitner et al.	1.95	-M/W	0.0	0.0	-0.25	1.2	0.84	1.05

The differential scattering cross section is given by

$$\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}} = \frac{1}{64\pi^3}\frac{1}{MM_\Delta}\frac{|\vec{k}'|}{E_k}\left[\frac{\Gamma(W)/2}{(W-M_\Delta)^2+\Gamma^2(W)/4}\right]\left\{\frac{G^2Cos^2\theta_c}{2}L_{\mu\nu}J^{\mu\nu}\right\}$$

with $$L_{\mu\nu} = \overline{\sum}\sum l_\mu^\dagger l_\nu = Tr[(\not{k}+m_\nu)\gamma_\mu(1-\gamma_5)(\not{k}'+m_l)\gamma_\nu(1-\gamma_5)]$$
$$= 8\left(k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu}\, k\cdot k' + i\varepsilon_{\mu\nu\alpha\beta}\, k^\alpha k'^\beta\right)$$

and $$J^{\mu\nu} = \overline{\sum}\sum J^{\mu^\dagger}J^\nu = Tr\left[(\not{p}+M)\tilde{O}^{\mu\alpha}P^{3/2}_{\mu\nu}O^{\beta\nu}\right]$$

Where $\tilde{O}^{\mu\alpha}$ is the weak N-Δ transition vertex, and $P^{3/2}_{\mu\nu}(P)$ is the Rarita Schwinger spin-3/2 projection operator given as

$$P^{3/2}_{\mu\nu}(P) = -\frac{\not{P}+M_\Delta}{2M_\Delta}\left[g_{\alpha\beta}-\frac{1}{3}\gamma_\alpha\gamma_\beta-\frac{2}{3M_\Delta^2}P_\alpha P_\beta+\frac{1}{3M_\Delta}(P_\alpha\gamma_\beta-\gamma_\alpha P_\beta)\right]$$

Γ(W) is Δ decay width taken to be energy dependent P-wave decay Width given as:

$$\Gamma(W) = \frac{1}{6\pi}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right)^2\frac{M}{W}\left|\vec{k}_\pi^{cm}\right|^3\Theta(W-M-m_\pi)$$

$$\left|\vec{k}_\pi^{cm}\right| = \frac{\sqrt{(W^2-m_\pi^2-M^2)^2-4m_\pi^2M^2}}{2W}$$

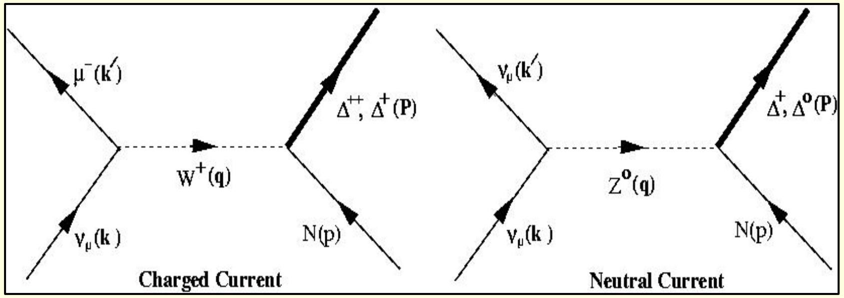
Pion momentum in the rest frame of resonance

Weak Production of Pion From Nuclei

1. Incoherent Weak Production of Pion
2. Coherent Weak Production of Pion

Incoherent Weak Production of Pion

$$\nu_\mu(k)+p(p)\rightarrow\mu^-(k')+\Delta^{++}(P)$$
$$\searrow p+\pi^+$$
$$\nu_\mu(k)+n(p)\rightarrow\mu^-(k')+\Delta^{+}(P)$$
$$\searrow n+\pi^+\,(p+\pi^0)$$



In the nucleus the neutrino interacts with a nucleon moving inside the nucleus of density $\rho(\vec{r})$ with its corresponding momentum constrained to be below its Fermi momentum $K_{F_{n,p}}(r)=\left[3\pi^2\rho_{n,p}(r)\right]^{1/3}$

The differential cross section for Δ production in local density approximation is written as

$$\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}}=\int\rho(r)d^3r\left[\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}}\right]_{free}$$

$$=\frac{G^2Cos^2\theta_c}{128\pi^3}\int\rho(r)d^3r\frac{|\vec{k}'|}{E_k}\frac{1}{MM_\Delta}\left[\frac{\Gamma(W)/2}{(W-M_\Delta)^2+\Gamma^2(W)/4}\right]\left\{L_{\mu\nu}J^{\mu\nu}\right\}$$

Nuclear Effects

- The nuclear medium effects in Δ production are important.
- In the nuclear medium the M_Δ and Γ_Δ are modified
- These are mainly due to following processes

✓In the nuclear medium $\Delta \to N\pi$, The final nucleons have to be above the Fermi momentum of the nucleon in the nucleus, thus inhibiting the decay

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

$$\hat{\Gamma} = \frac{1}{6\pi}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right)^2 \frac{M}{W}\left|\vec{k}_\pi^{\,cm}\right|^3 F(k_F, E_\Delta, k_\Delta)$$

$$F(k_F, E_\Delta, k_\Delta) = \frac{k_\Delta\left|\vec{k}_\pi^{\,cm}\right| + E_\Delta E_p'^{\,cm} - E_F W}{2k_\Delta\left|\vec{k}_\pi^{\,cm}\right|}$$

Pauli Correction factor

k_F is the Fermi momentum and k_Δ is the Δ momentum

✓ Additional decay channels:

- $\Delta N \rightarrow NN$, $\Delta NN \rightarrow NNN$ (Two and three body absorption process through which Δ disappears in the nuclear medium without producing pions
- $\Delta N \rightarrow \pi NN$ (Two body absorption process gives rise to more pions)

$$\tilde{\Gamma} \rightarrow \tilde{\Gamma} - 2\,\mathrm{Im}\Sigma_{\Delta}$$

$$M_{\Delta} \rightarrow M_{\Delta} + \mathrm{Re}\Sigma_{\Delta}$$

with
$$\mathrm{Re}\Sigma_{\Delta} = 40.0\left(\frac{\rho}{\rho_0}\right) MeV$$

The imaginary part of the delta self energy is parameterized as

$$-\,\mathrm{Im}\Sigma_{\Delta} = C_Q\left(\frac{\rho}{\rho_0}\right)^{\alpha} + C_{A2}\left(\frac{\rho}{\rho_0}\right)^{\beta} + C_{A3}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

C_Q ~ accounts for the $\Delta N \rightarrow \pi N N$ process

C_{A2}~ accounts for two-body absorption process $\Delta N \rightarrow N N$

C_{A3}~ accounts for three-body absorption process $\Delta N \rightarrow N N N$

The Coefficients C_Q , C_{A2} , C_{A3} , α , β and γ (=2 β) are parameterized in the range $80 < T_\pi < 320$ MeV (where T_π is the pion kinetic energy) as

$$C(T_\pi) = ax^2 + bx + c \qquad x = \frac{T_\pi}{m_\pi}$$

Coefficients	C_Q(MeV)	C_{A2}(MeV)	C_{A3}(MeV)	α	$\beta=2\gamma$
a	*-5.19*	*1.06*	*-13.46*	*0.382*	*-0.038*
b	*15.35*	*-6.64*	*46.17*	*-1.322*	*0.204*
c	*2.06*	*22.66*	*-20.34*	*1.466*	*0.613*

The Differential Scattering Cross Section Modifies to

$$\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}} = \frac{G^2 Cos^2\theta_c}{128\pi^3}\int \rho(r)d^3r \frac{|\vec{k}'|}{E_k}\frac{1}{MM_\Delta}\left[\frac{\frac{\tilde{\Gamma}}{2} - \mathrm{Im}\Sigma_\Delta}{(W - M_\Delta - \mathrm{Re}\Sigma_\Delta)^2 + \left(\frac{\tilde{\Gamma}}{2} - \mathrm{Im}\Sigma_\Delta\right)}\right]\{L_{\mu\nu}J^{\mu\nu}\}$$

For Charged Current Incoherent one π^+ production from proton target

$$\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}} = \frac{G^2 Cos^2\theta_c}{128\pi^3}\int \rho_p(r)d^3r \frac{|\vec{k}'|}{E_k}\frac{1}{MM_\Delta}\left[\frac{\frac{\tilde{\Gamma}}{2} - C_Q\left(\frac{\rho}{\rho_0}\right)^\alpha}{(W - M_\Delta - \mathrm{Re}\Sigma_\Delta)^2 + \left(\frac{\tilde{\Gamma}}{2} - \mathrm{Im}\Sigma_\Delta\right)}\right]\{L_{\mu\nu}J^{\mu\nu}\}$$

For Charged Current Incoherent one π^+ production from nuclear target

$$\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}} = \frac{G^2 Cos^2\theta_c}{128\pi^3}\int d^3r \frac{|\vec{k}'|}{E_k}\frac{1}{MM_\Delta}\left[\frac{\frac{\tilde{\Gamma}}{2} - C_Q\left(\frac{\rho}{\rho_0}\right)^\alpha}{(W - M_\Delta - \mathrm{Re}\Sigma_\Delta)^2 + \left(\frac{\tilde{\Gamma}}{2} - \mathrm{Im}\Sigma_\Delta\right)}\right]\left[\rho_p(r) + \frac{1}{9}\rho_n(r)\right]\{L_{\mu\nu}J^{\mu\nu}\}$$

As $\Delta^{++} \to p + \pi^+$ and $\Delta^+ \to p + \pi^0\,(n + \pi^+)$

Final State Interactions (FSI)

FSI for Incoherent Pion Production

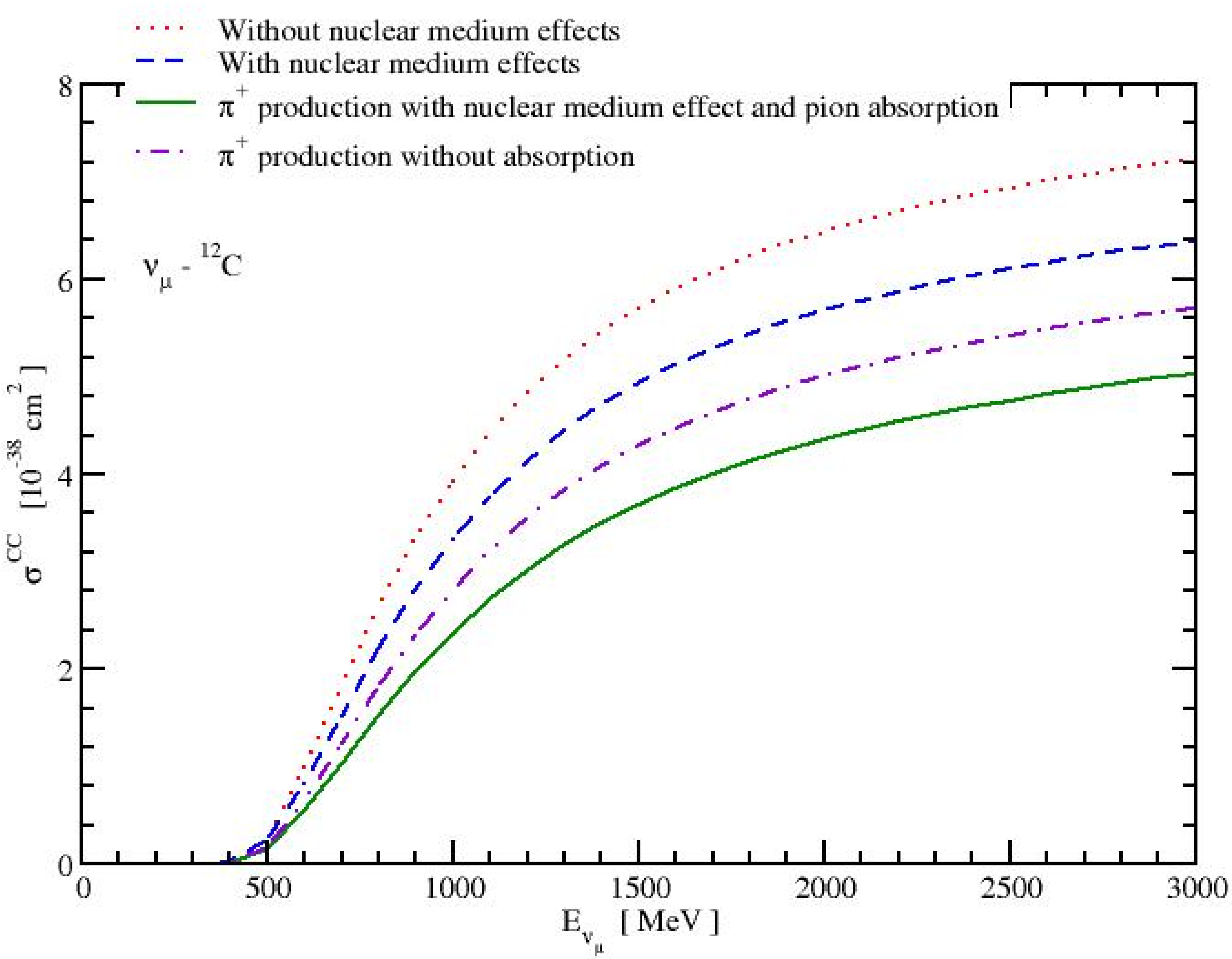
The pions which are produced in these processes while traveling inside the nucleus can be absorbed, can change direction, energy, charge, or even produce more pions due to elastic and charge exchange scattering with the nucleons present in the nucleus through strong interactions.

The effect of final state interaction (FSI) on the weak production cross section for pions are estimated with the help of a Monte Carlo simulation for propagation of pions in the nuclear medium using as the basic input the probabilities per unit length for each of these channels to happens.

We have used the Monte Carlo simulation code provided by the M. J. Vicente Vacas for final state interaction of pions.

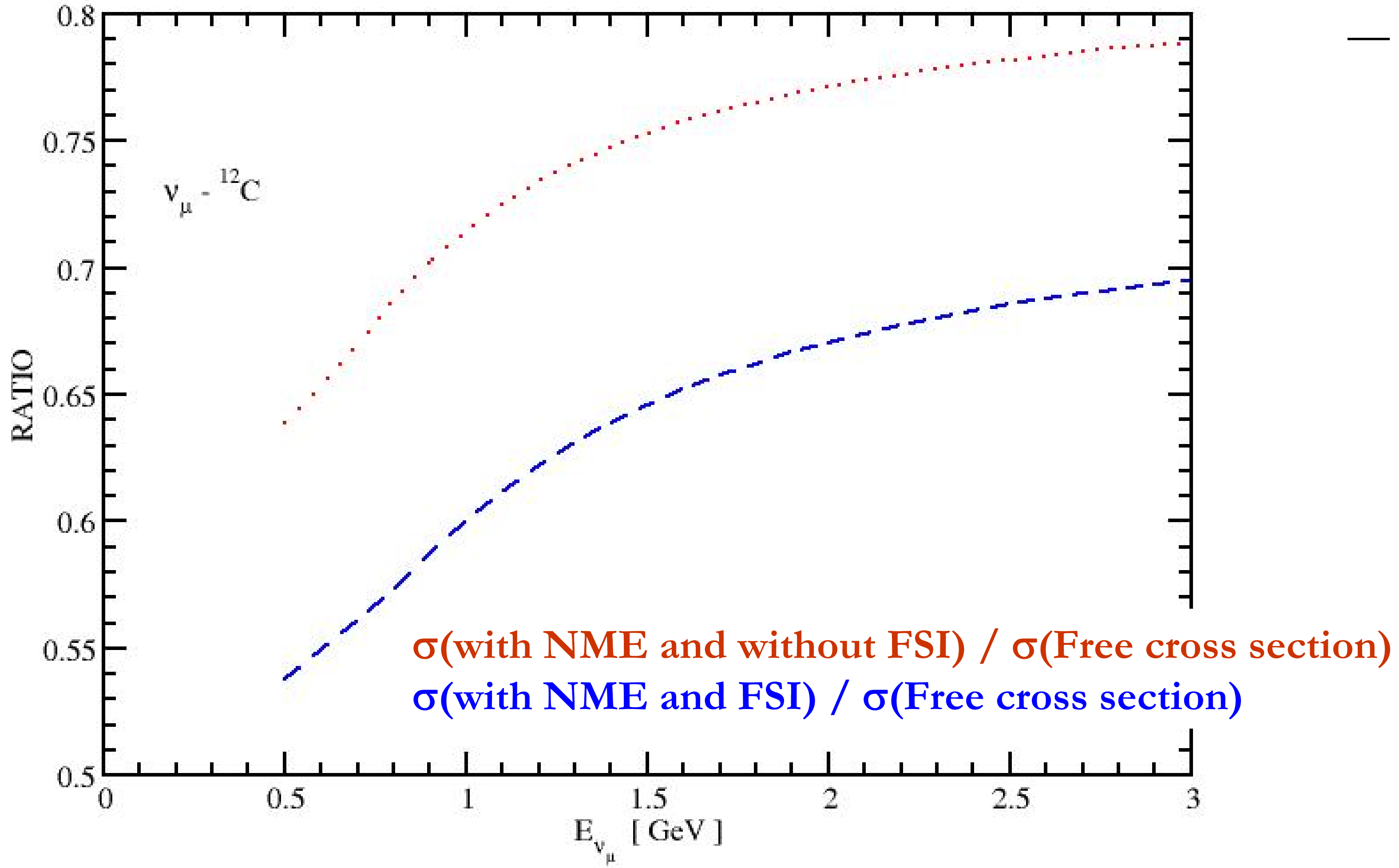
Results For Neutrino Induced Incoherent Process

Charged Current Incoherent Pion Production



Phys. Rev. D 74, 073008 (2006)

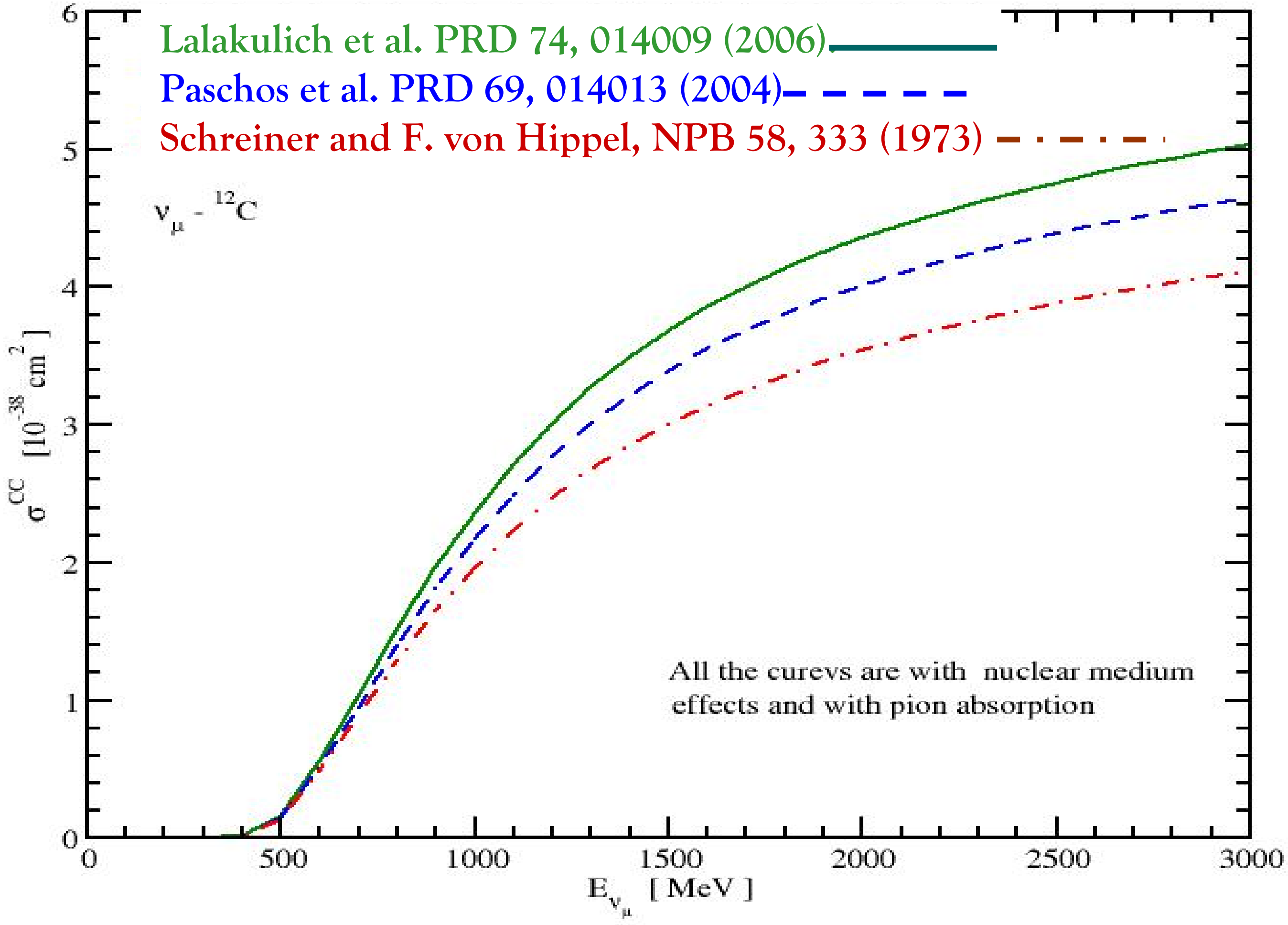
Charged Current Incoherent Pion Production



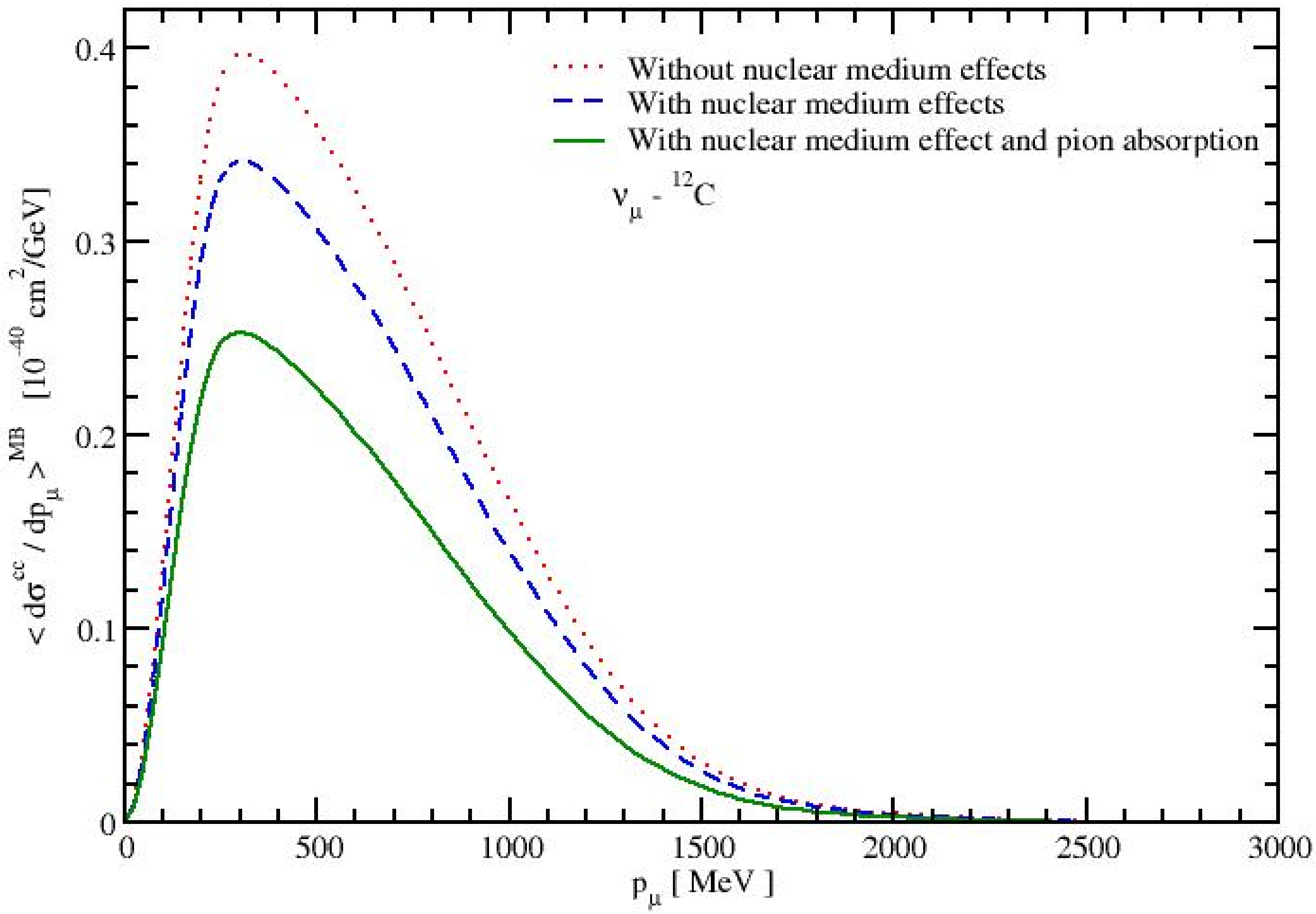
NME: Nuclear Medium Effects, FSI: Final State Interaction

Charged Current Incoherent Pion Production

Form Factor Dependence

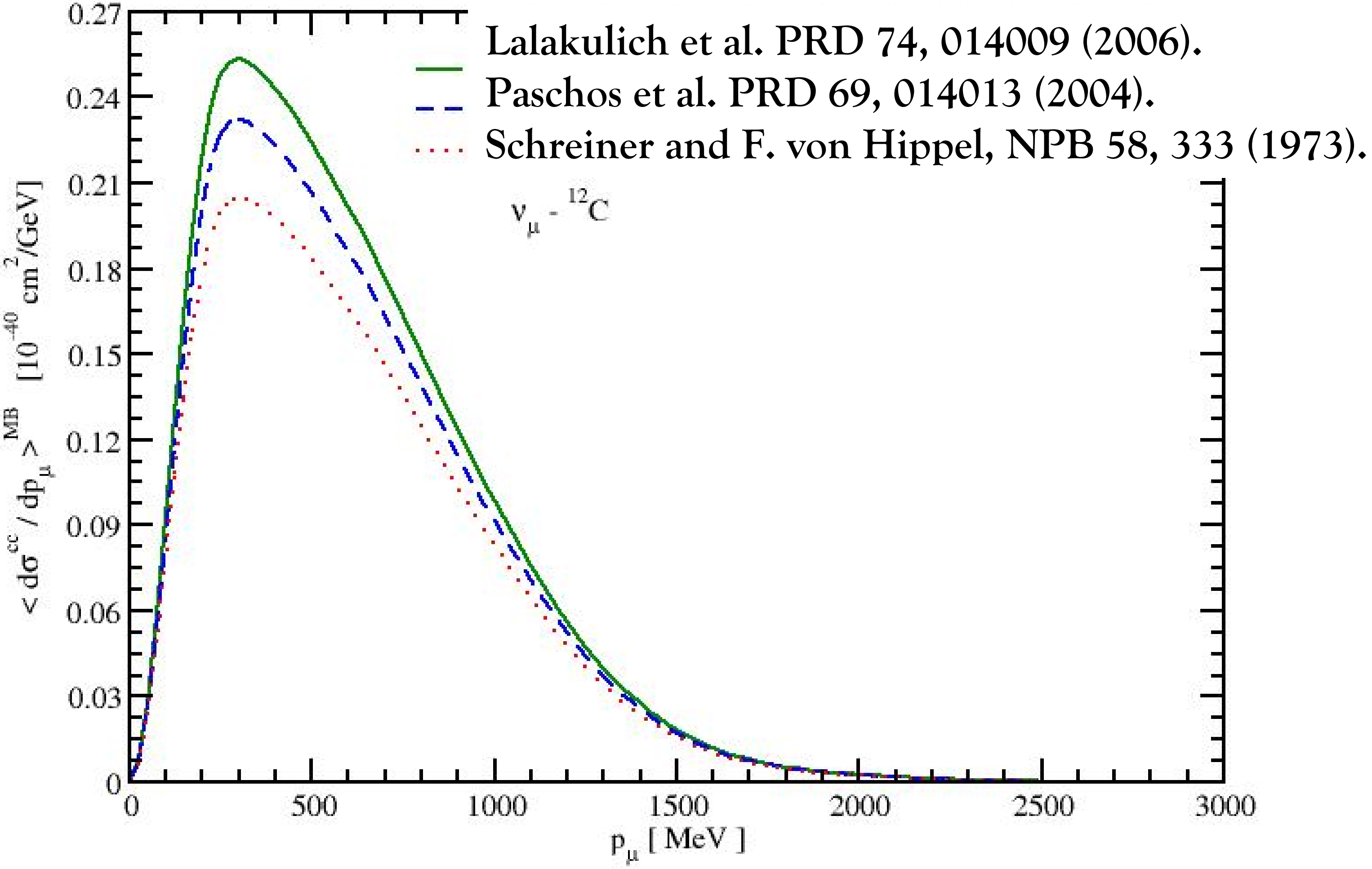


Charged Current Incoherent Lepton Production averaged over MiniBooNE neutrino spectrum

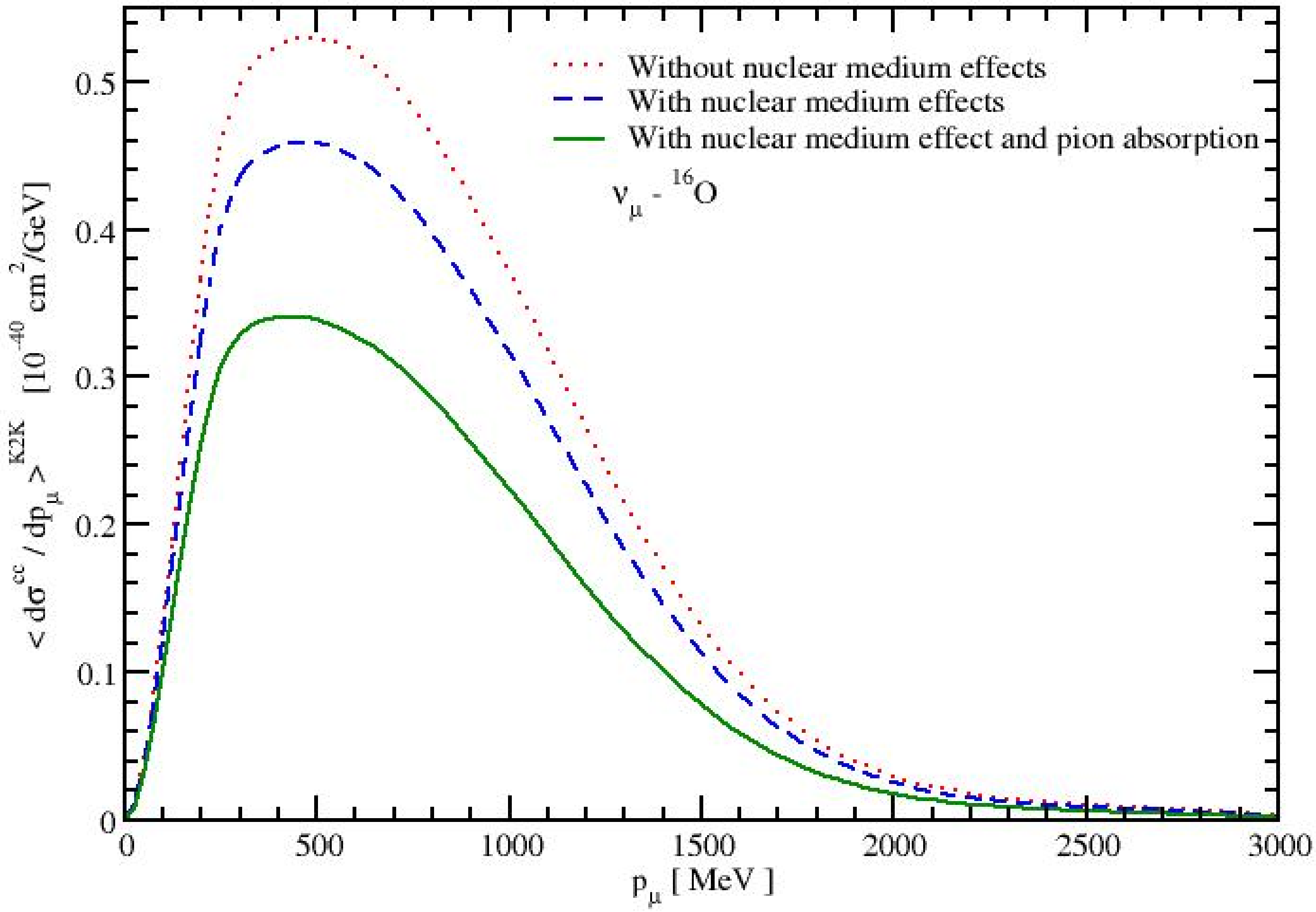


Charged Current Incoherent Lepton Production

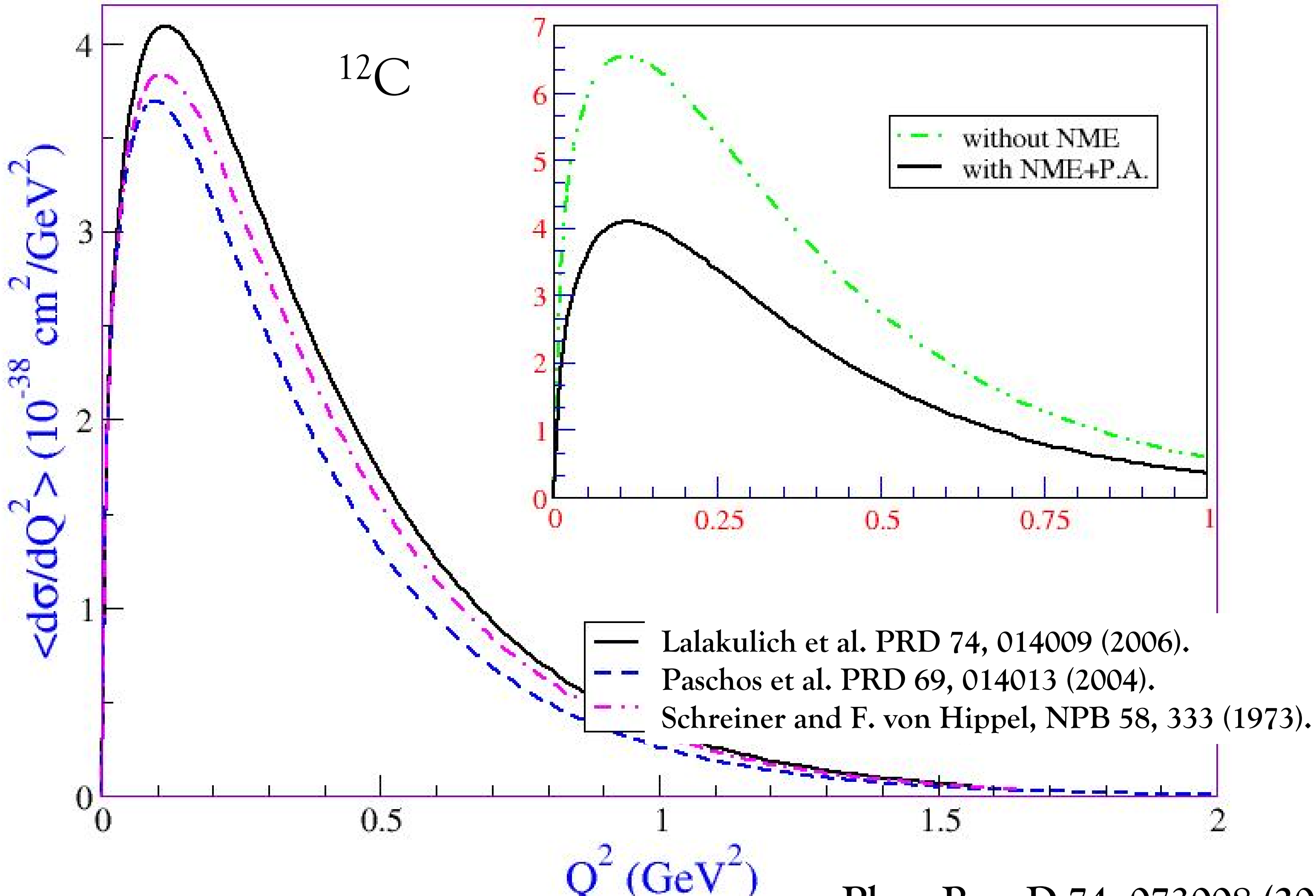
Form Factor Dependence



Charged Current Incoherent Lepton Production averaged over K2K neutrino spectrum

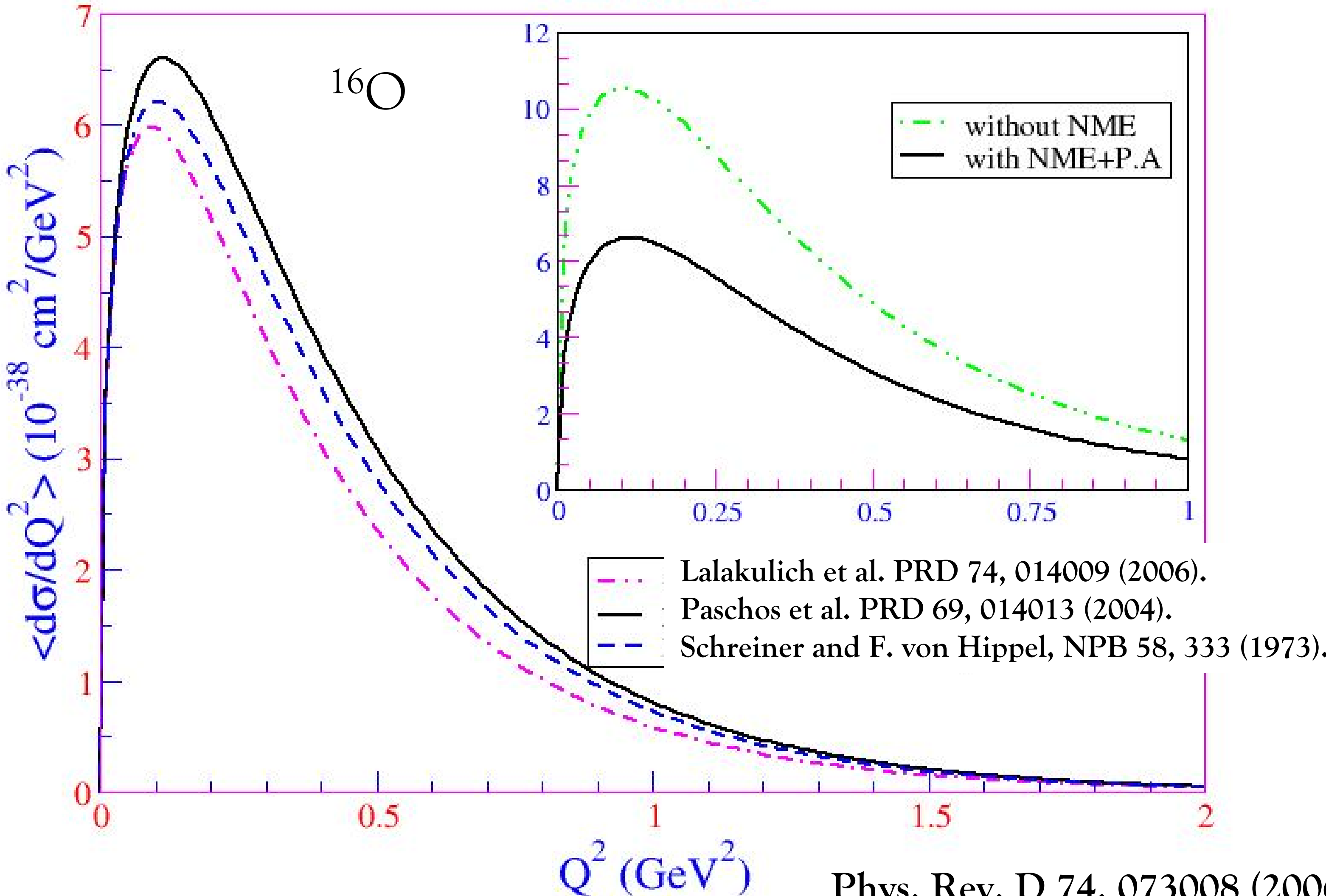


Charged Current Incoherent Lepton Production averaged over MiniBooNE neutrino spectrum



Phys. Rev. D 74, 073008 (2006)

Charged Current Incoherent Lepton Production averaged over K2K neutrino spectrum



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Comparison With Experiments

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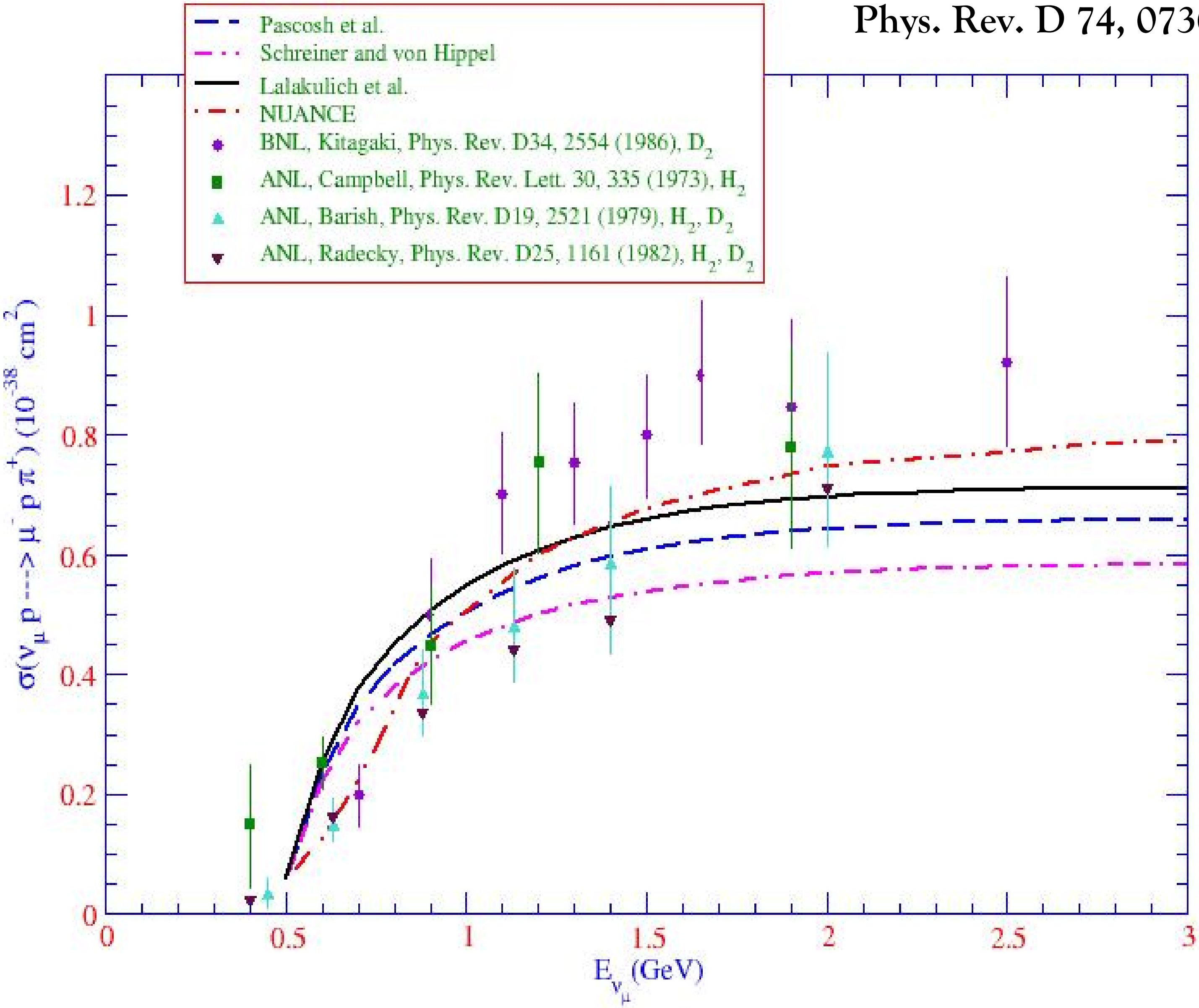
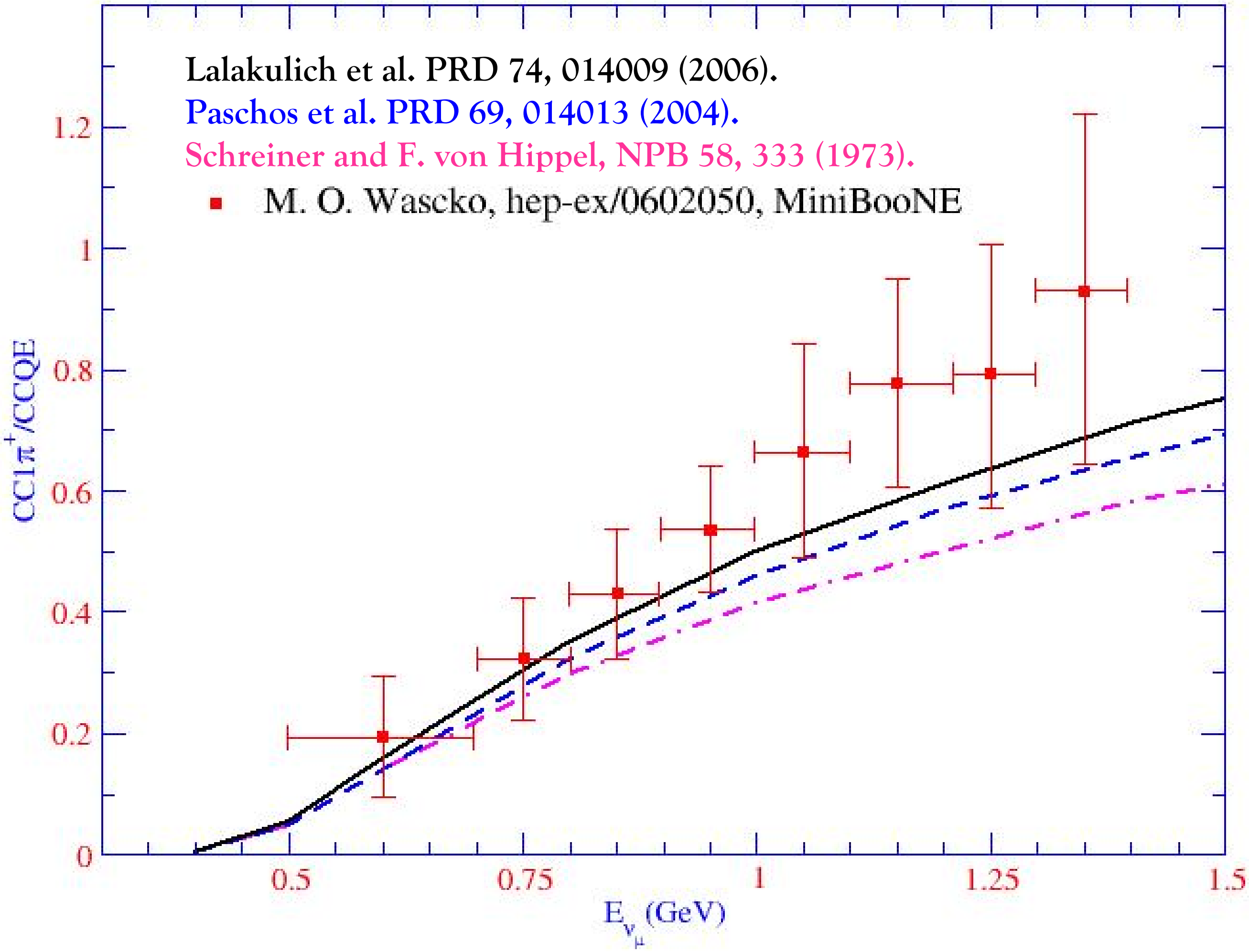


Ratio of C.C.1π^+/CCQE



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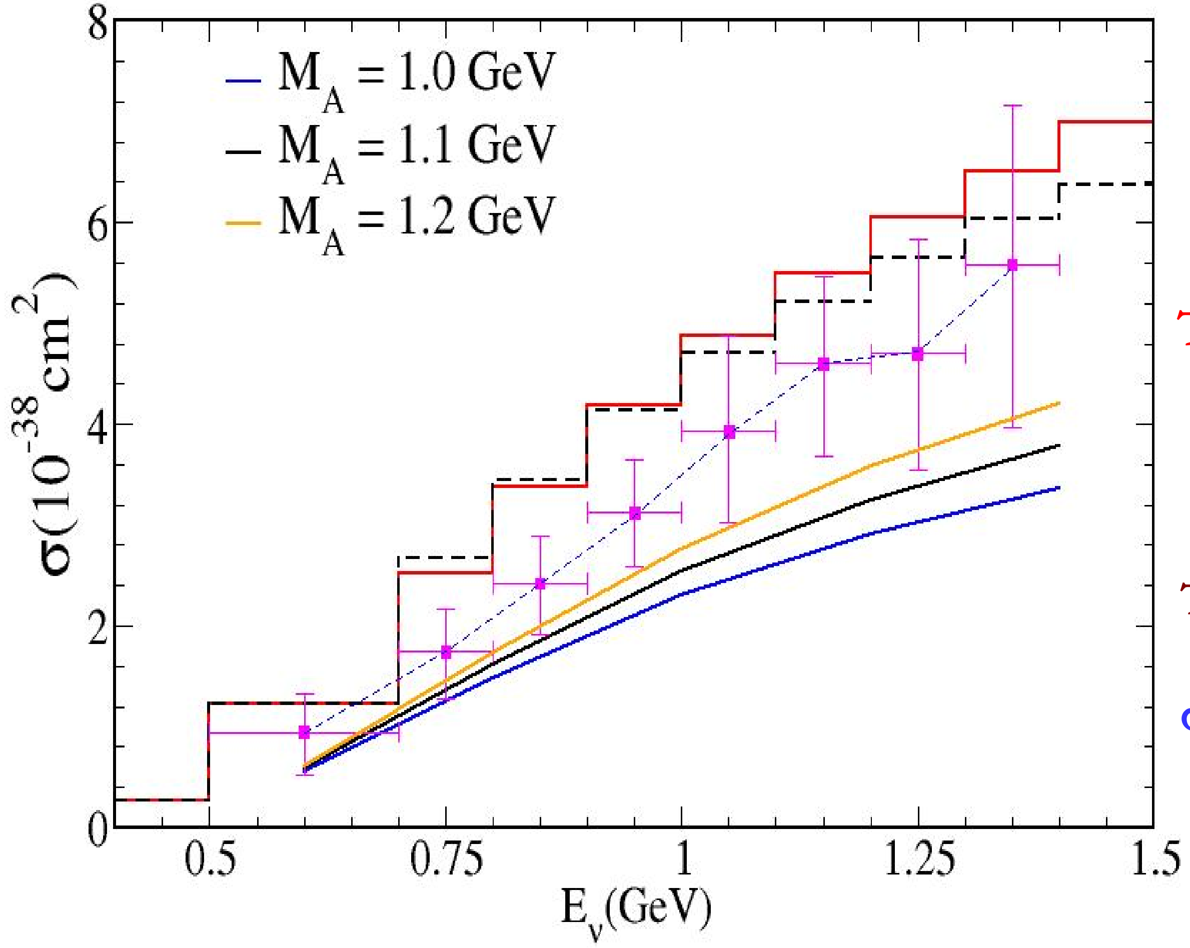


The dashed (solid) stairs are the Cross sections from NEUGEN(NUANCE) MC generators.
Experimental points Are the MiniBooNE results.

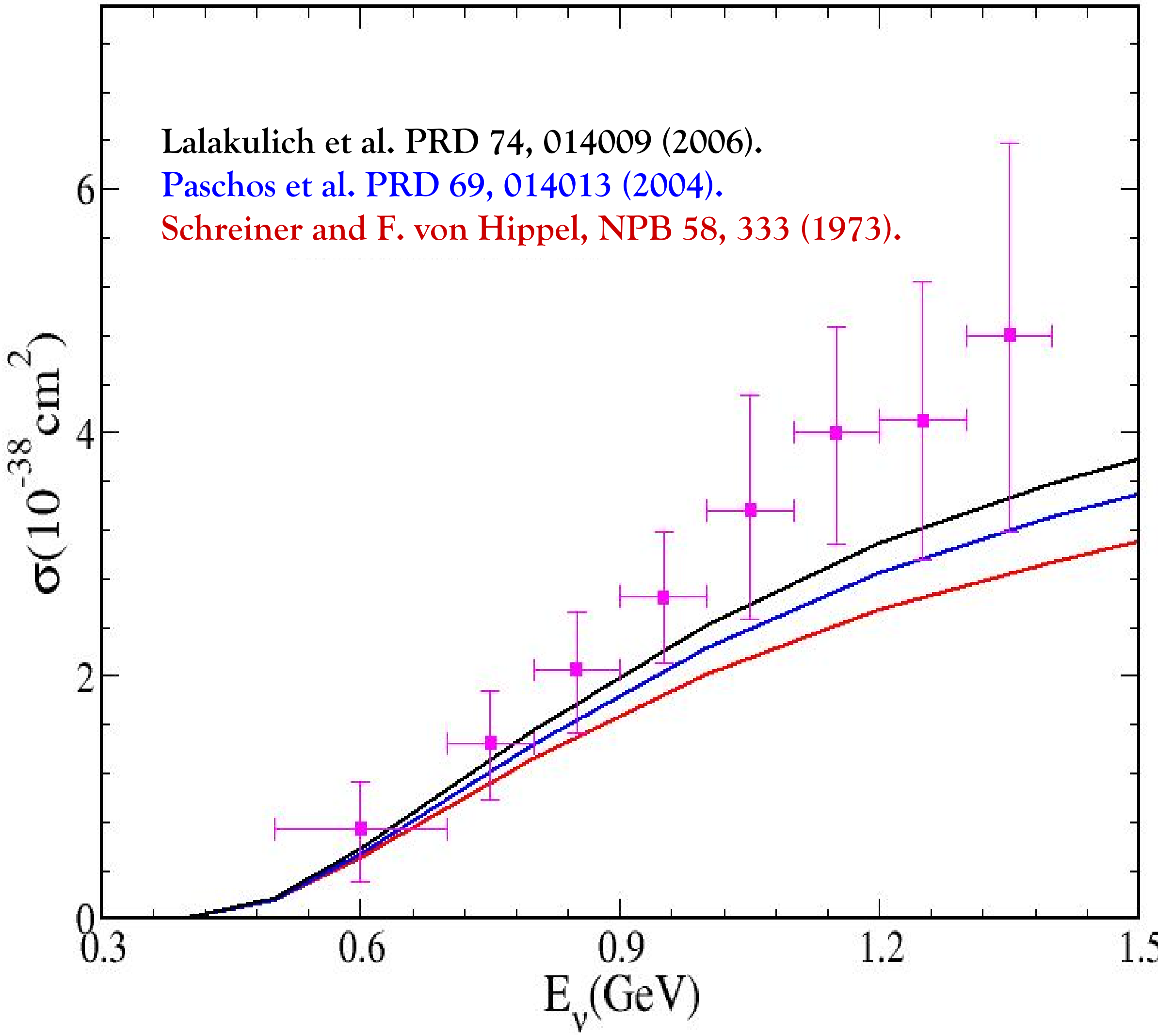
The theoretical curves show the $CC1\pi^+$ cross section using Lalakulich et al. N-Δ transition form factors.

The dashed line is $CC1\pi^+$ =

$$\sigma(\mathrm{CCQE})_{\text{without RPA}} \times \left.\frac{CC1\pi^+}{CCQE}\right|_{MB}$$

With M_A = 1.05 GeV

Phys. Rev. D 74, 073008 (2006)



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

The experimental points show

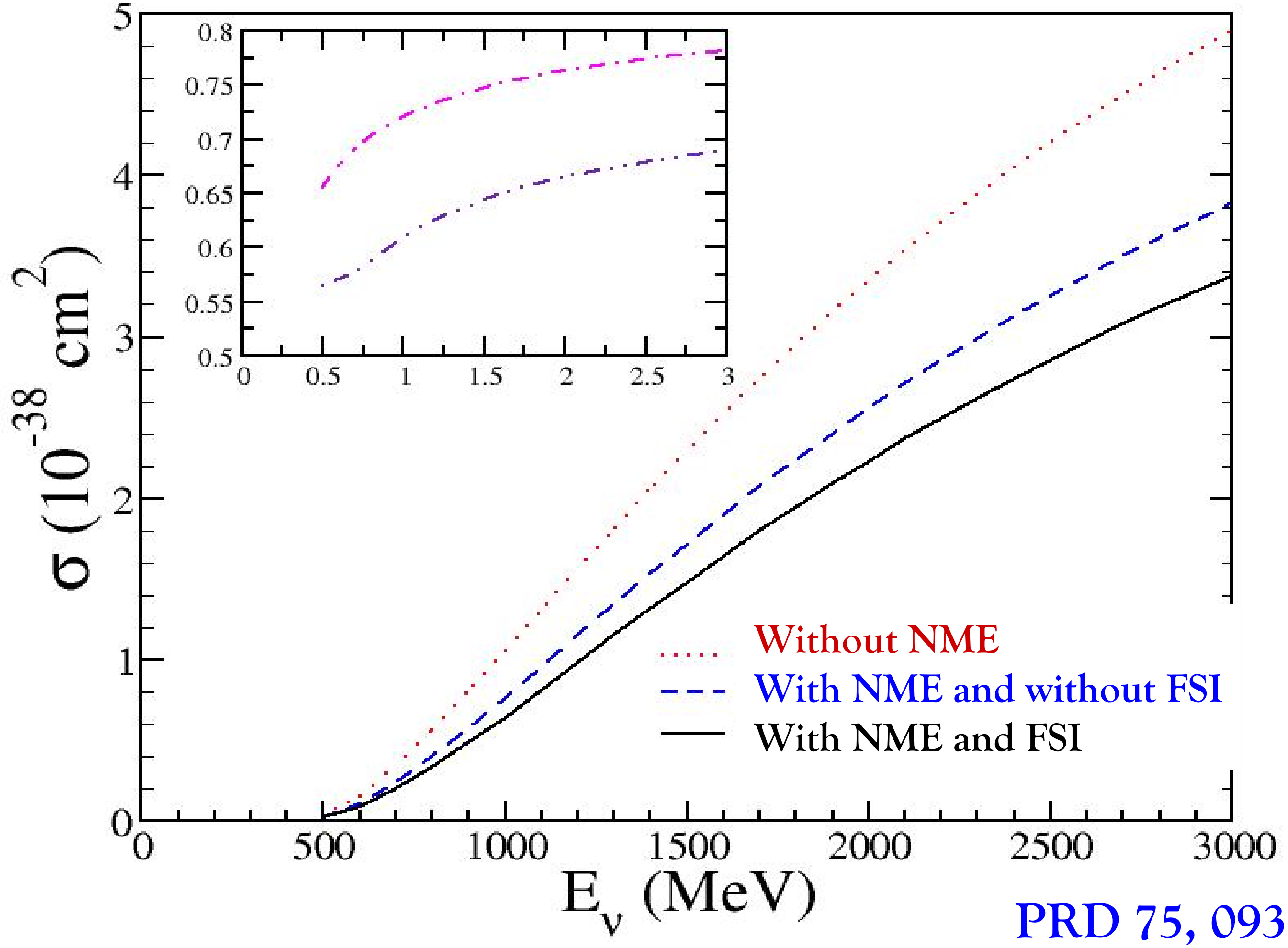
$$CC1\pi^+ = \sigma(CCQE)_{\text{with RPA}} \times \left.\frac{CC1\pi^+}{CCQE}\right|_{MB}$$

With M_A = 1.05 GeV

Phys. Rev. D 74, 073008 (2006)

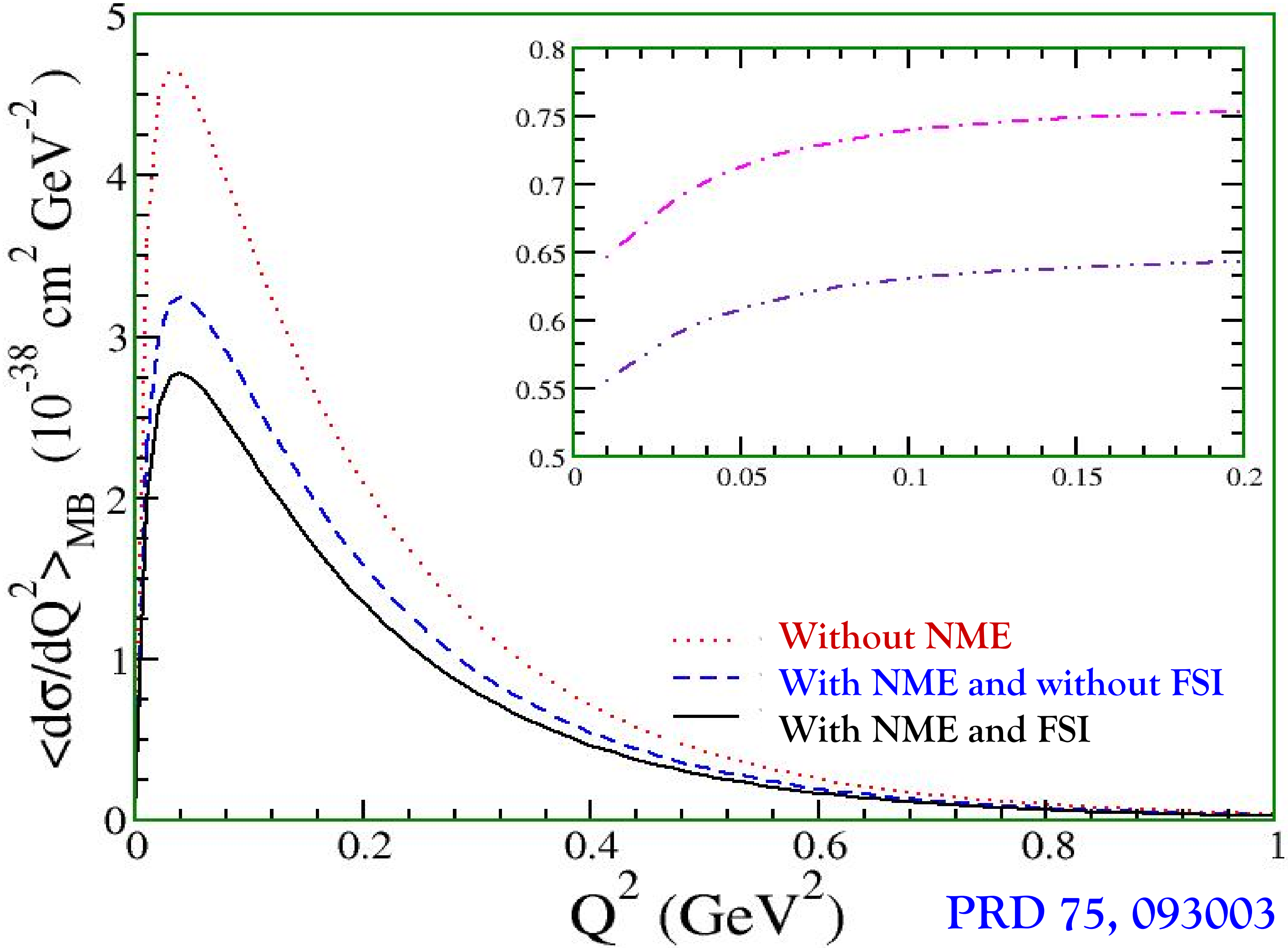
Results For Antineutrino Induced Inelastic Process

The cross section for inelastic charged current lepton production accompanied by a pion induced by anti ν_μ on ^{12}C target.



PRD 75, 093003 (2007)

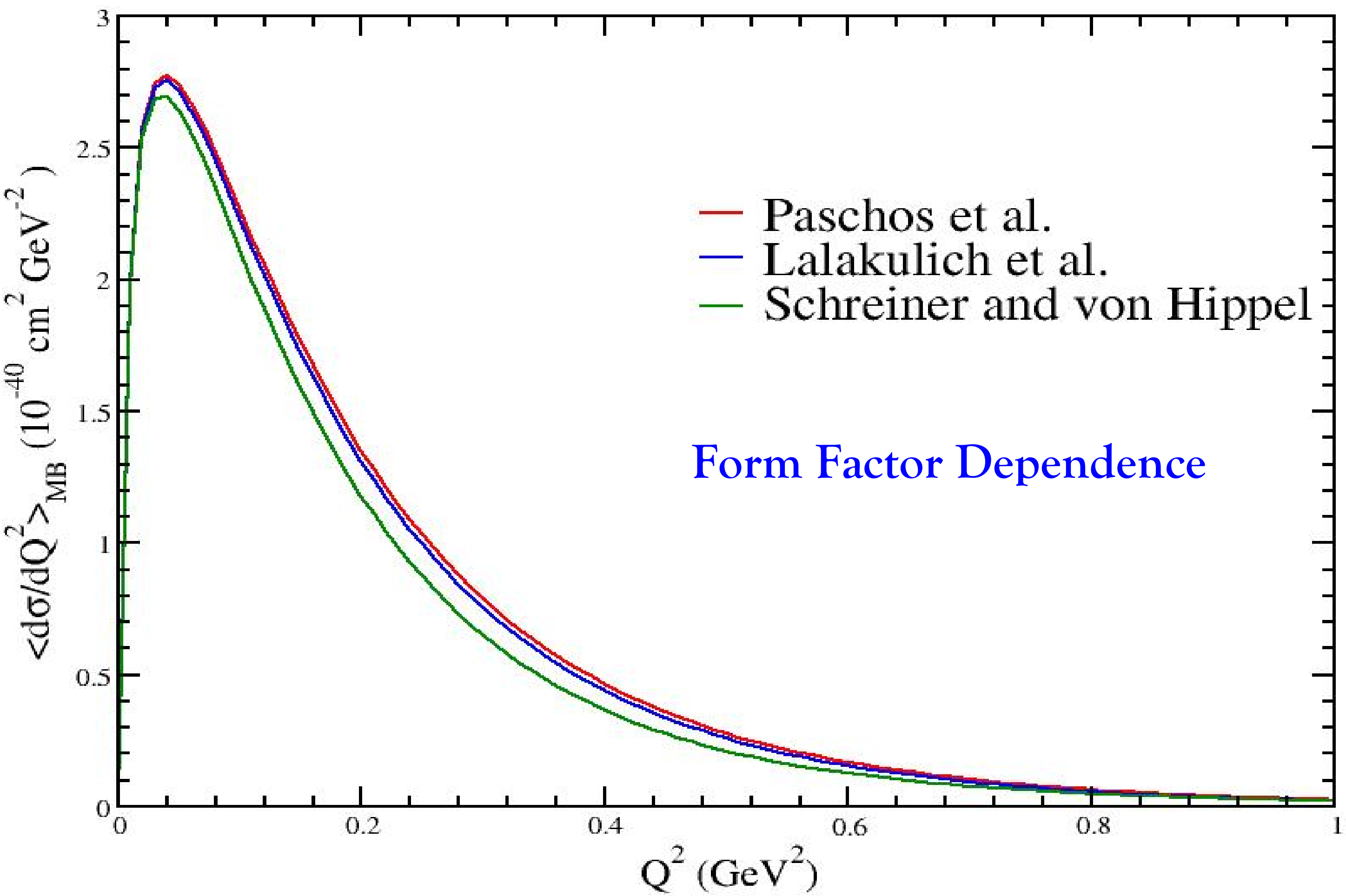
The Q^2 –Distribution for anti ν_μ on ^{12}C target averaged over MiniBooNE Spectrum for the inelastic charged current lepton production process accompanied by a pion



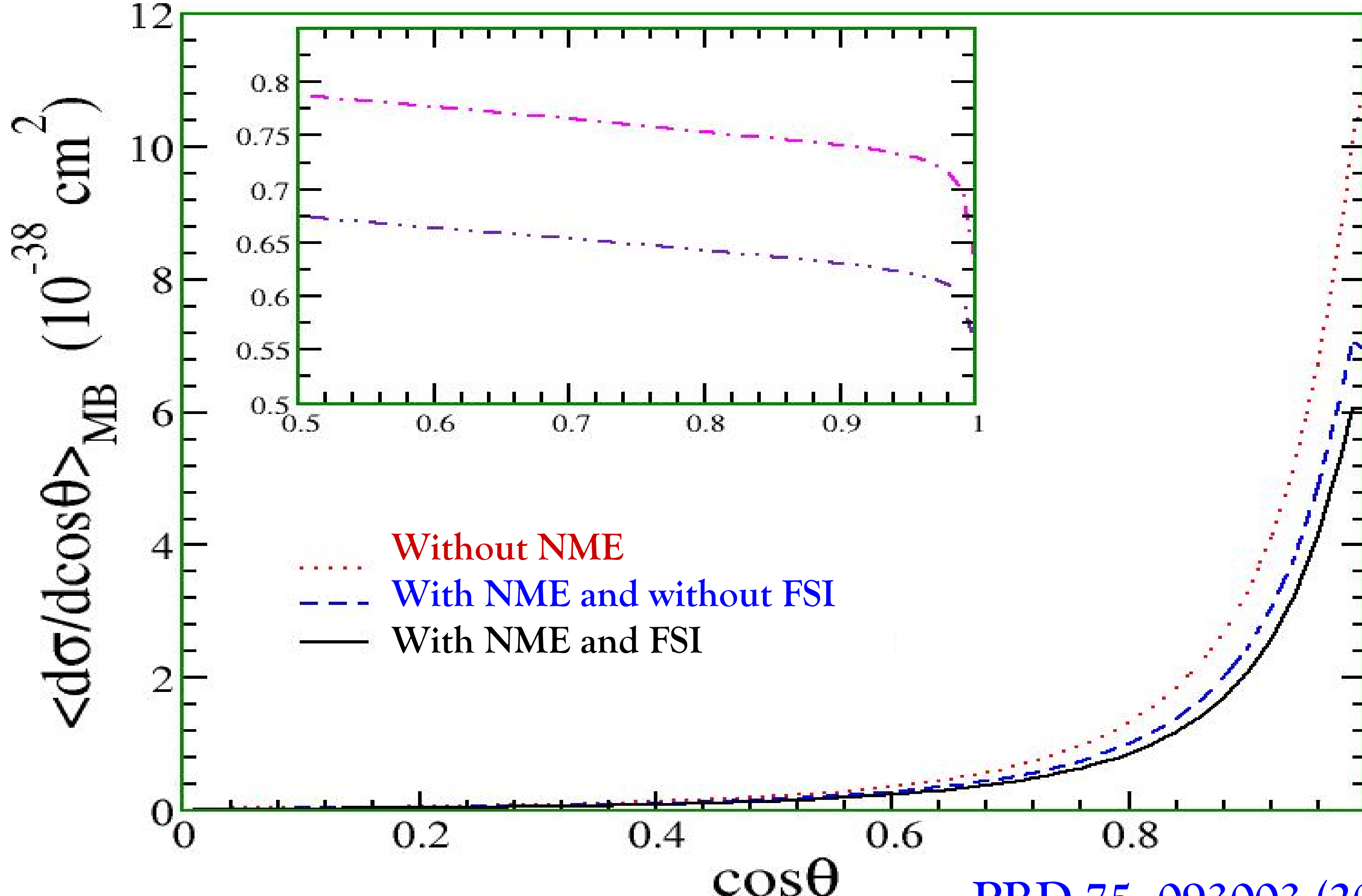
PRD 75, 093003 (2007)

The Q^2 –Distribution for anti ν_μ on ^{12}C target averaged over MiniBooNE Spectrum for the inelastic charged current lepton production process accompanied by a pion

PRD 75, 093003 (2007)



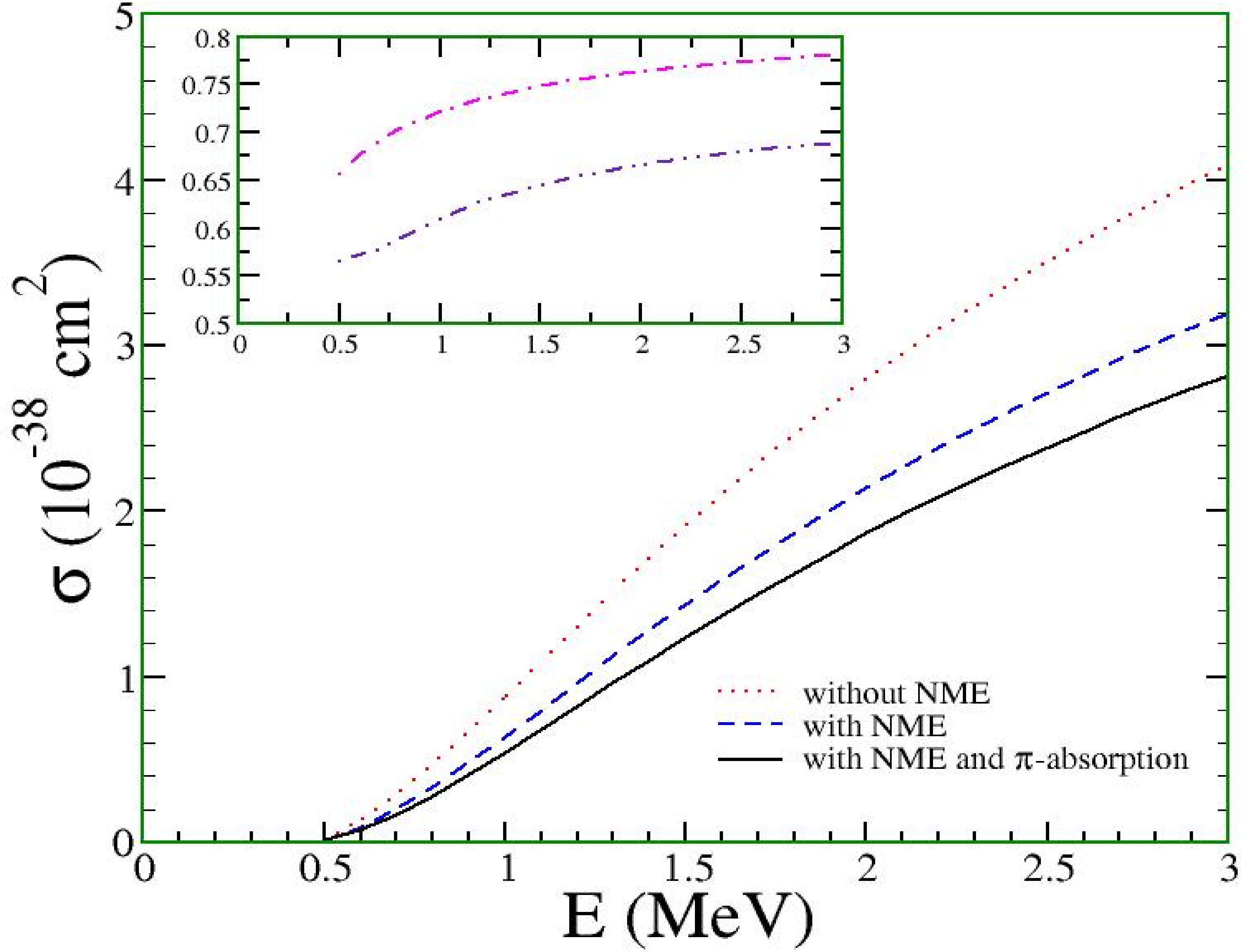
The Angular distribution for anti ν_μ on ^{12}C target averaged over MiniBooNE Spectrum for the inelastic charged current lepton production process accompanied by a pion



PRD 75, 093003 (2007)

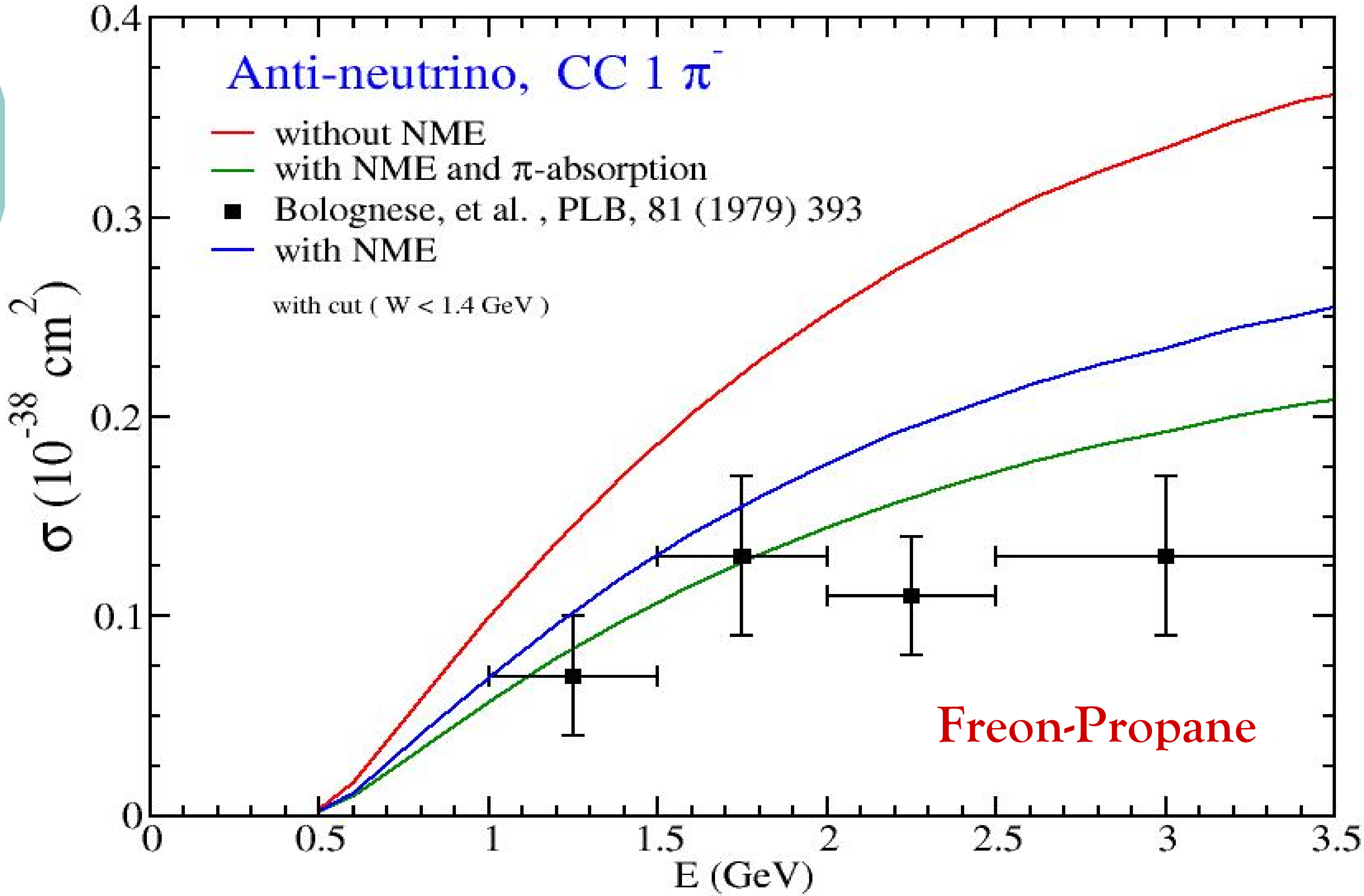
Inelastic charged current one π^- production induced by anti ν_μ on ^{12}C target.

PRD 75, 093003 (2007)



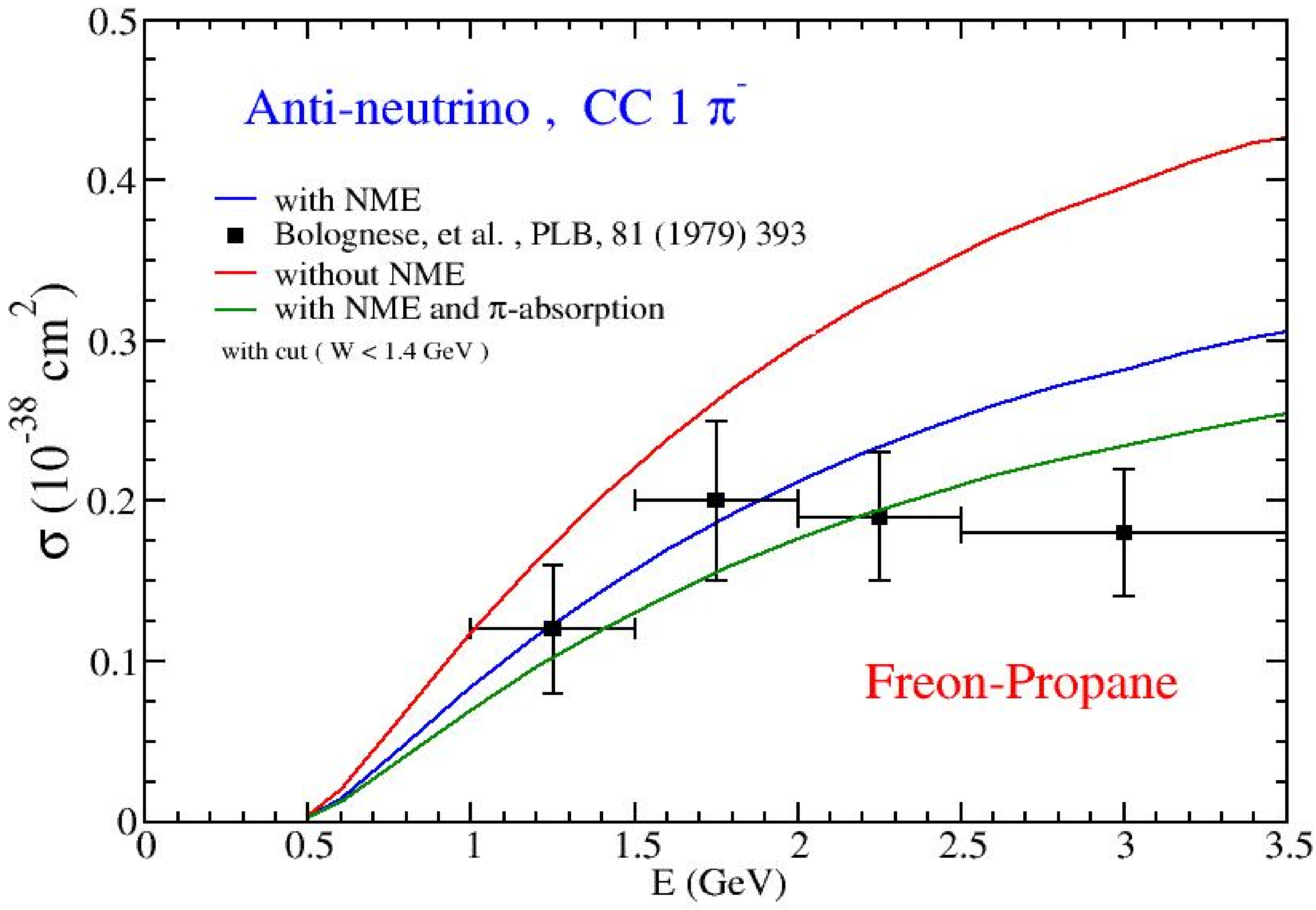
Inelastic charged current one π^- production per neutron induced by anti ν_μ on ^{12}C target.

PRD 75, 093003 (2007)



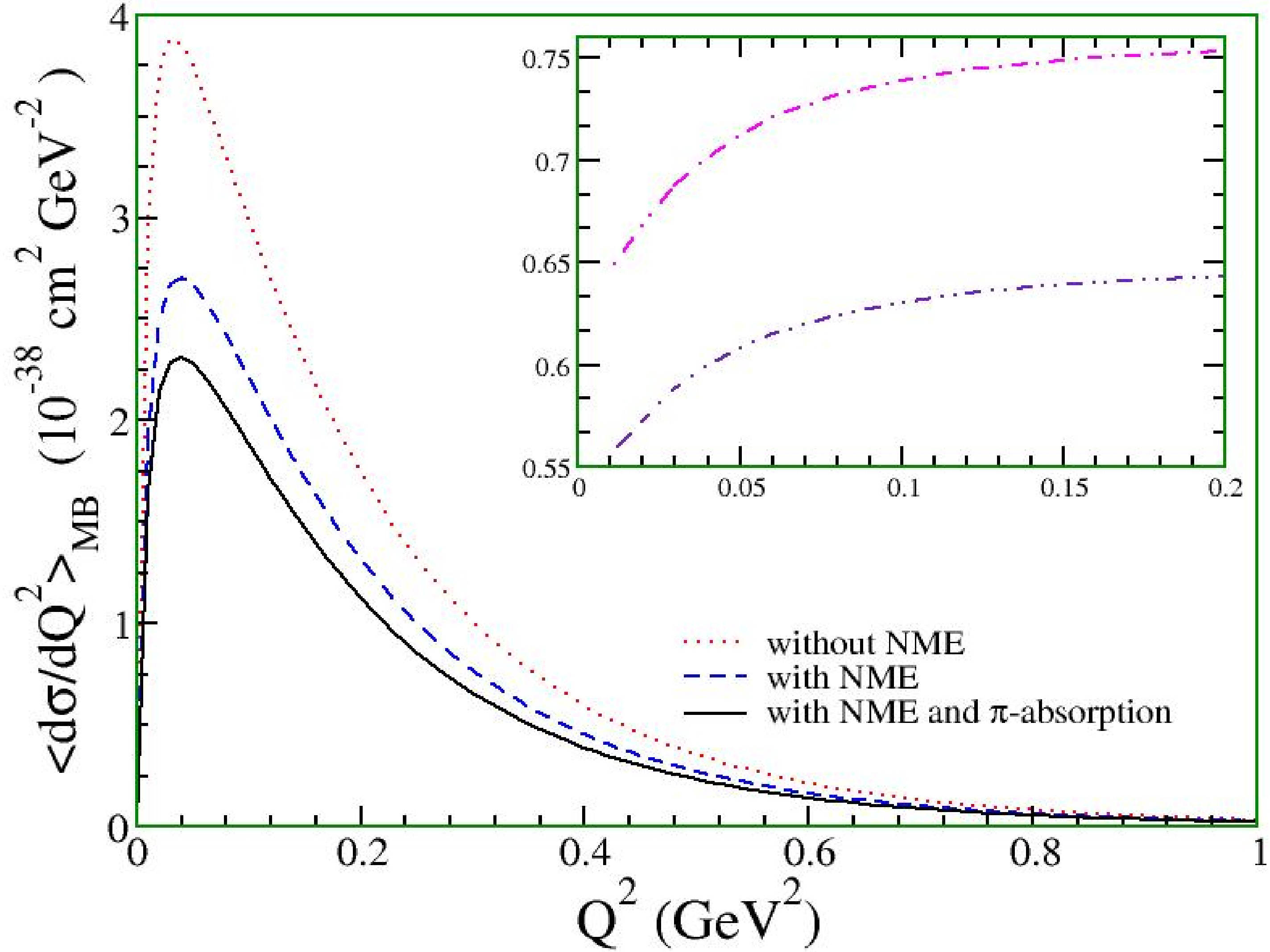
Inelastic charged current one π^- production per nucleon induced by anti ν_μ on ^{12}C target.

PRD 75, 093003 (2007)



The Q^2 –Distribution for anti ν_μ on ^{12}C target averaged over MiniBooNE Spectrum for the inelastic charged current lepton production process accompanied by a π^-.

PRD 75, 093003 (2007)



The Angular distribution for anti ν_μ on ^{12}C target averaged over MiniBooNE Spectrum for the inelastic charged current lepton production process accompanied by a π^-.

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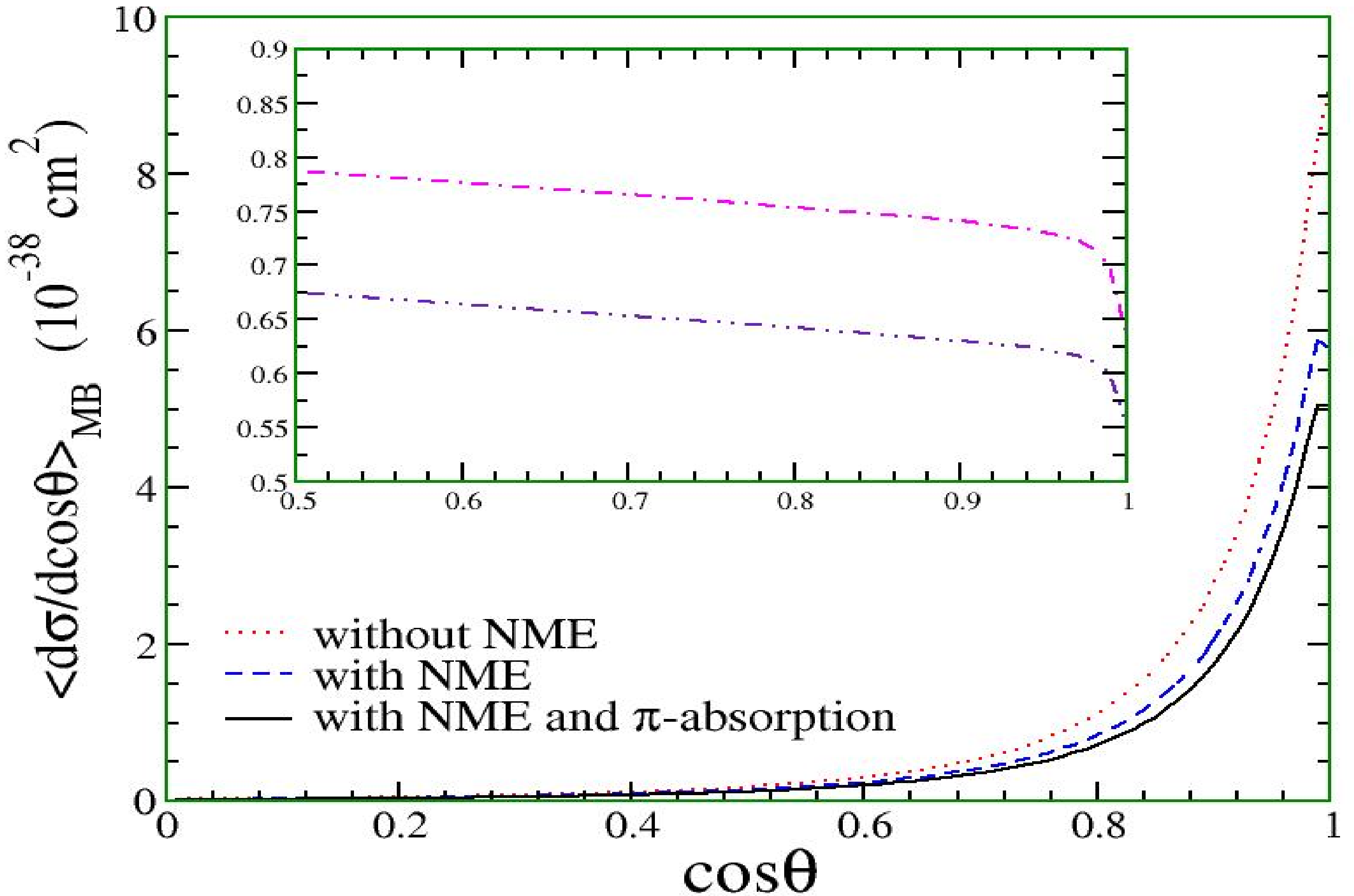
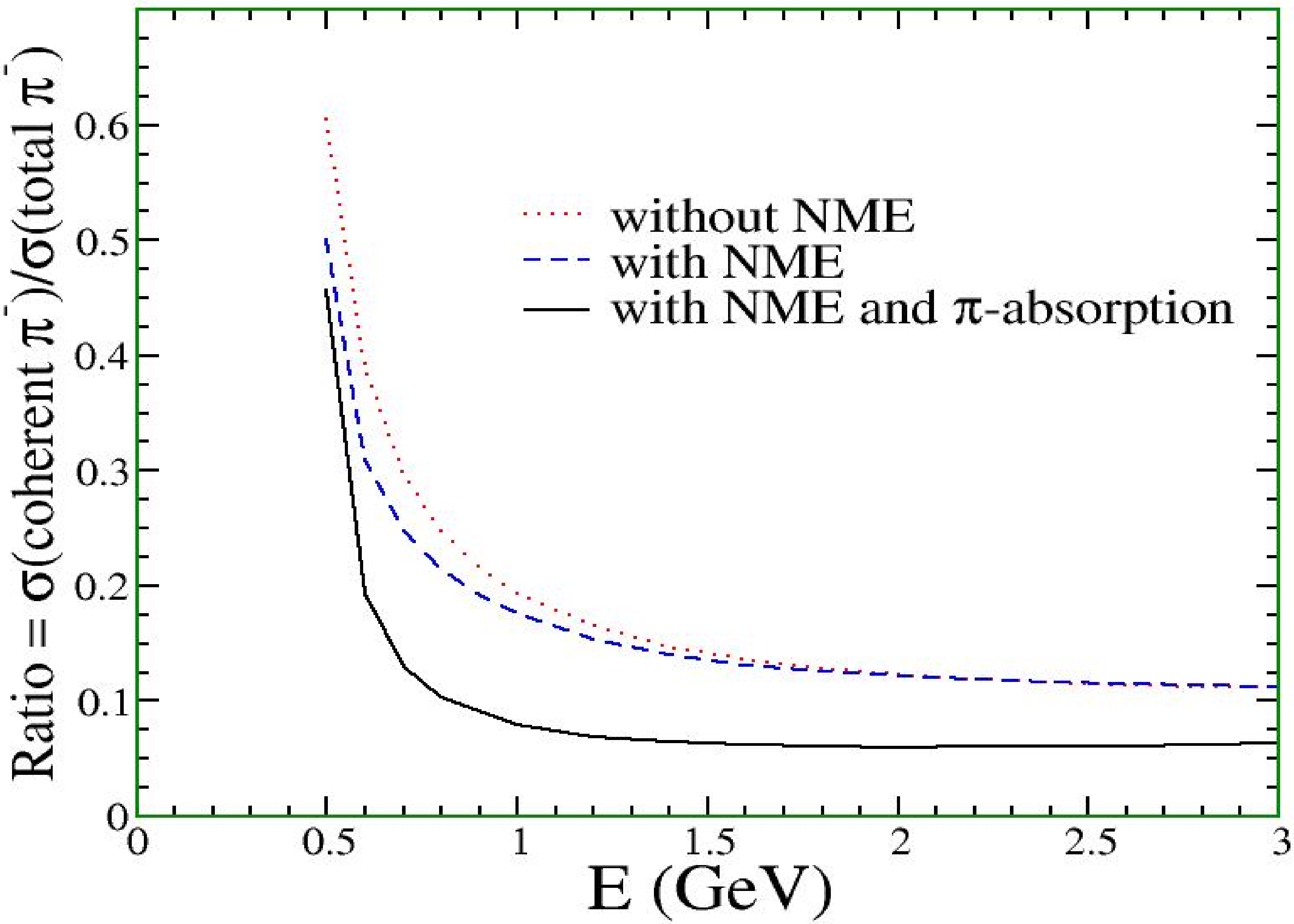
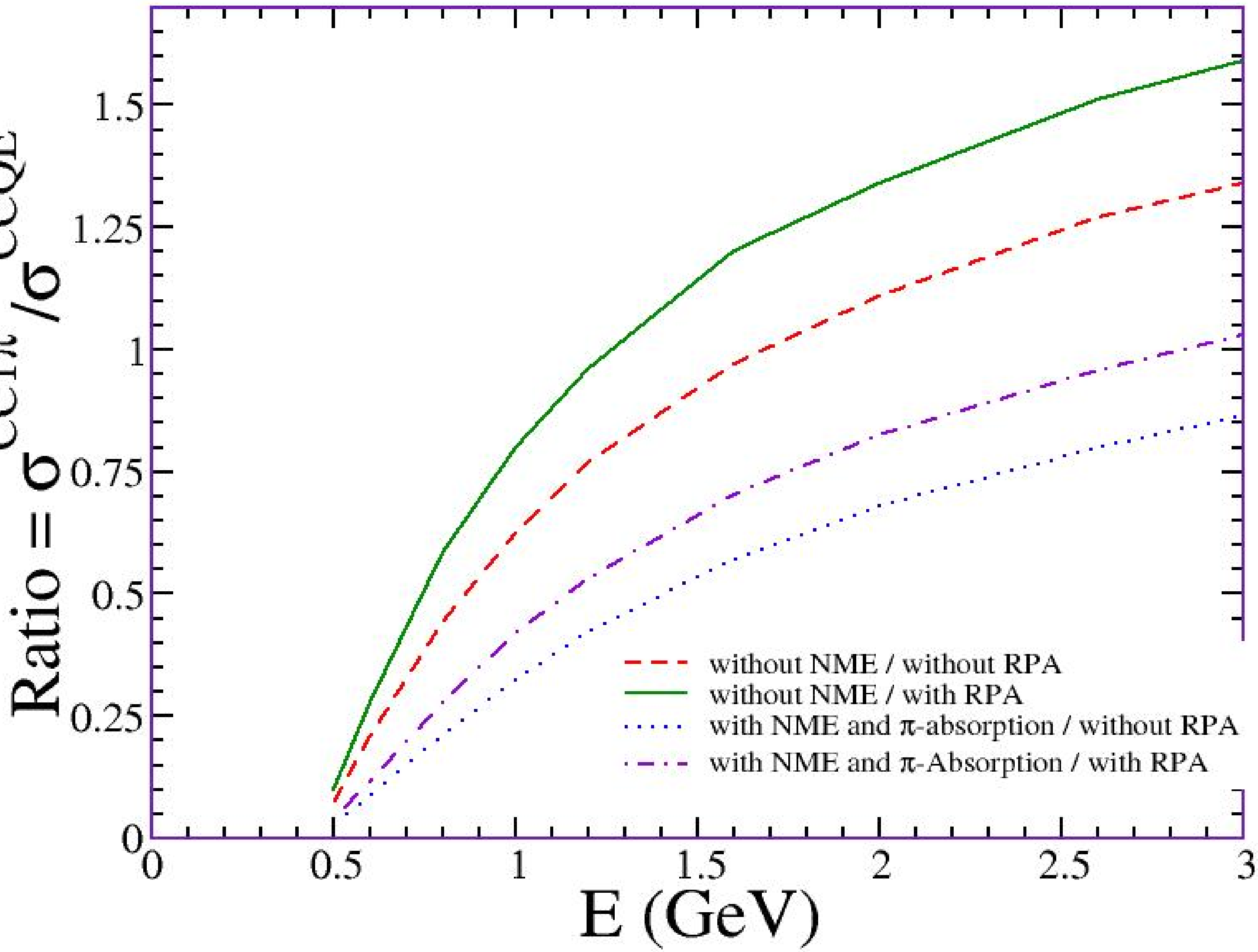


Ratio of Coherent charged current $1\pi^-$ production cross Section to the total charged current $1\pi^-$ production cross Section (Incoherent + Coherent) PRD 75, 093003 (2007)





Ratio = $\sigma^{CC1\pi^-}/\sigma^{CCQE}$
E (GeV)
0
0.25
0.5
0.75
1
1.25
1.5
0
0.5
1
1.5
2
2.5
3
without NME / without RPA
without NME / with RPA
with NME and π-absorption / without RPA
with NME and π-Absorption / with RPA

Qusielastic Production of Hyperons

-

$$\bar{\nu}_\ell + p \to \ell^+ + \Lambda$$

$$\bar{\nu}_\ell + p \to \ell^+ + \Sigma^0$$

$$\bar{\nu}_\ell + n \to \ell^+ + \Sigma^-$$

$$\langle Y(p')|V_\mu|N(p)\rangle = \bar{u}_Y(p')\left[f_1(q^2)\gamma_\mu + f_2(q^2) i\sigma_{\mu\nu}\frac{q^\nu}{M+M_Y} + f_3(q^2)\frac{q_\mu}{M_Y}\right]u_N(p)$$

$$\langle Y(p')|A_\mu|N(p)\rangle = \bar{u}_Y(p')\left[g_1(q^2)\gamma_\mu + g_2(q^2) i\sigma_{\mu\nu}\frac{q^\nu}{M+M_Y} + g_3(q^2)\frac{q_\mu}{M_Y}\right]\gamma^5 u_N(p)$$

Transitions	$g_1(q^2)$
$n \to p$	$g_A(q^2)$
$p \to \Lambda$	$-\sqrt{\frac{3}{2}}\frac{(1+2x)}{3} g_A(q^2)$
$n \to \Sigma^-$	$(1-2x) g_A(q^2)$

Transitions	$f_1(q^2)$	$f_2(q^2)$
$n \to p$	$f_1^p(q^2) - f_1^n(q^2)$	$f_2^p(q^2) - f_2^n(q^2)$
$p \to \Lambda$	$-\sqrt{\frac{3}{2}} f_1^p(q^2)$	$-\sqrt{\frac{3}{2}} f_2^p(q^2)$
$n \to \Sigma^-$	$-\left(f_1^p(q^2) + 2 f_1^n(q^2)\right)$	$-\left(f_2^p(q^2) + 2 f_2^n(q^2)\right)$

$$f_1^{p,n}(q^2) = \left(1 - \frac{q^2}{4M^2}\right)^{-1}\left[G_E^{p,n}(q^2) - \frac{q^2}{4M^2} G_M^{p,n}(q^2)\right]$$

$$f_2^{p,n}(q^2) = \left(1 - \frac{q^2}{4M^2}\right)^{-1}\left[G_M^{p,n}(q^2) - G_E^{p,n}(q^2)\right]$$

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

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

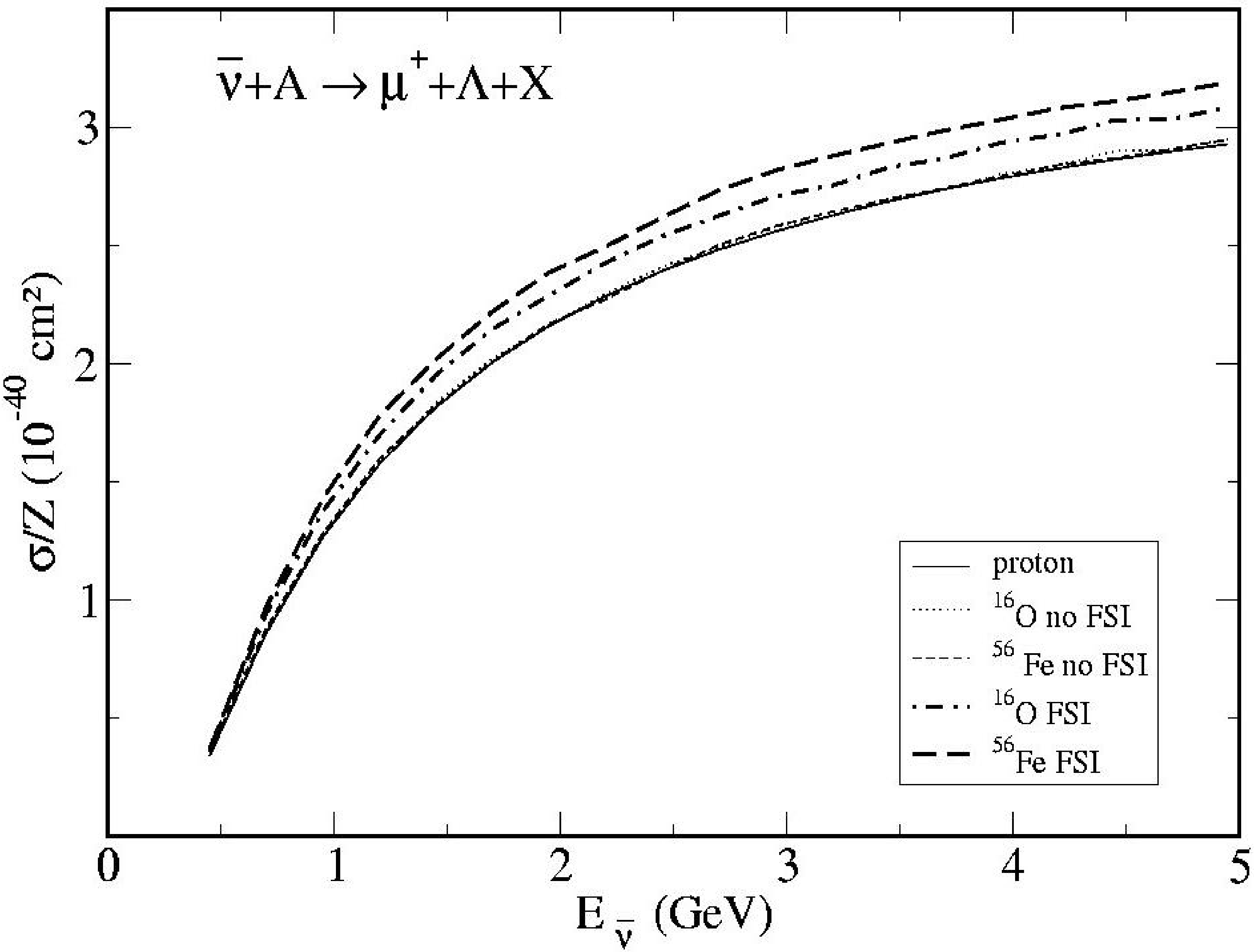
$$G_E^n(q^2) = \left(\frac{q^2}{4M^2}\right)\mu_n G_E^p(q^2)\xi_n ; \xi_n = \left(1 - \lambda_n \frac{q^2}{4M^2}\right)^{-1}$$

$$F_1^A(q^2) = F(0)\left(1 - \frac{q^2}{M_A^2}\right)^{-2}, F(0) = 0.463$$

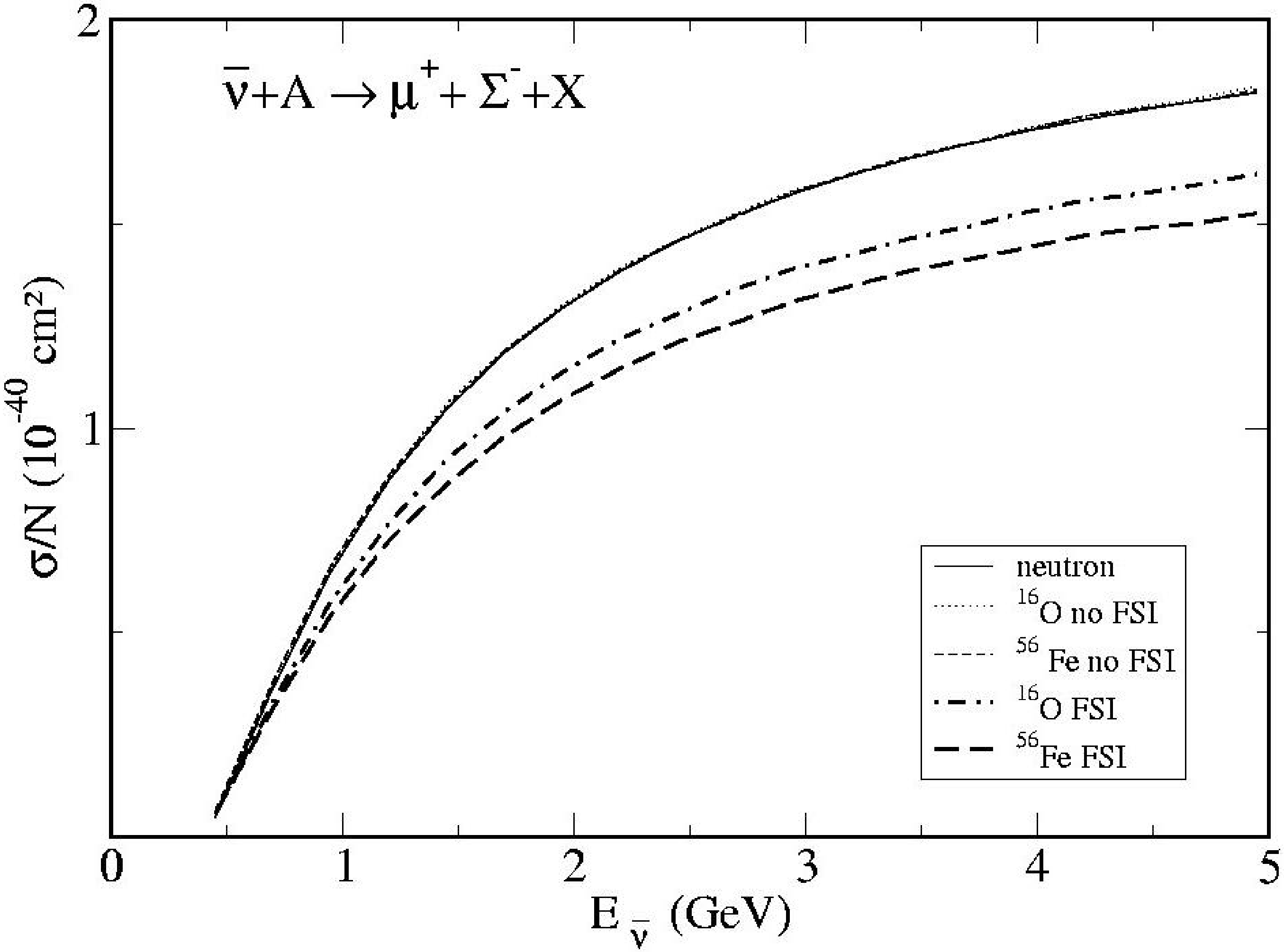
$$D_1^A(q^2) = D(0)\left(1 - \frac{q^2}{M_A^2}\right)^{-2}, D(0) = 0.804$$

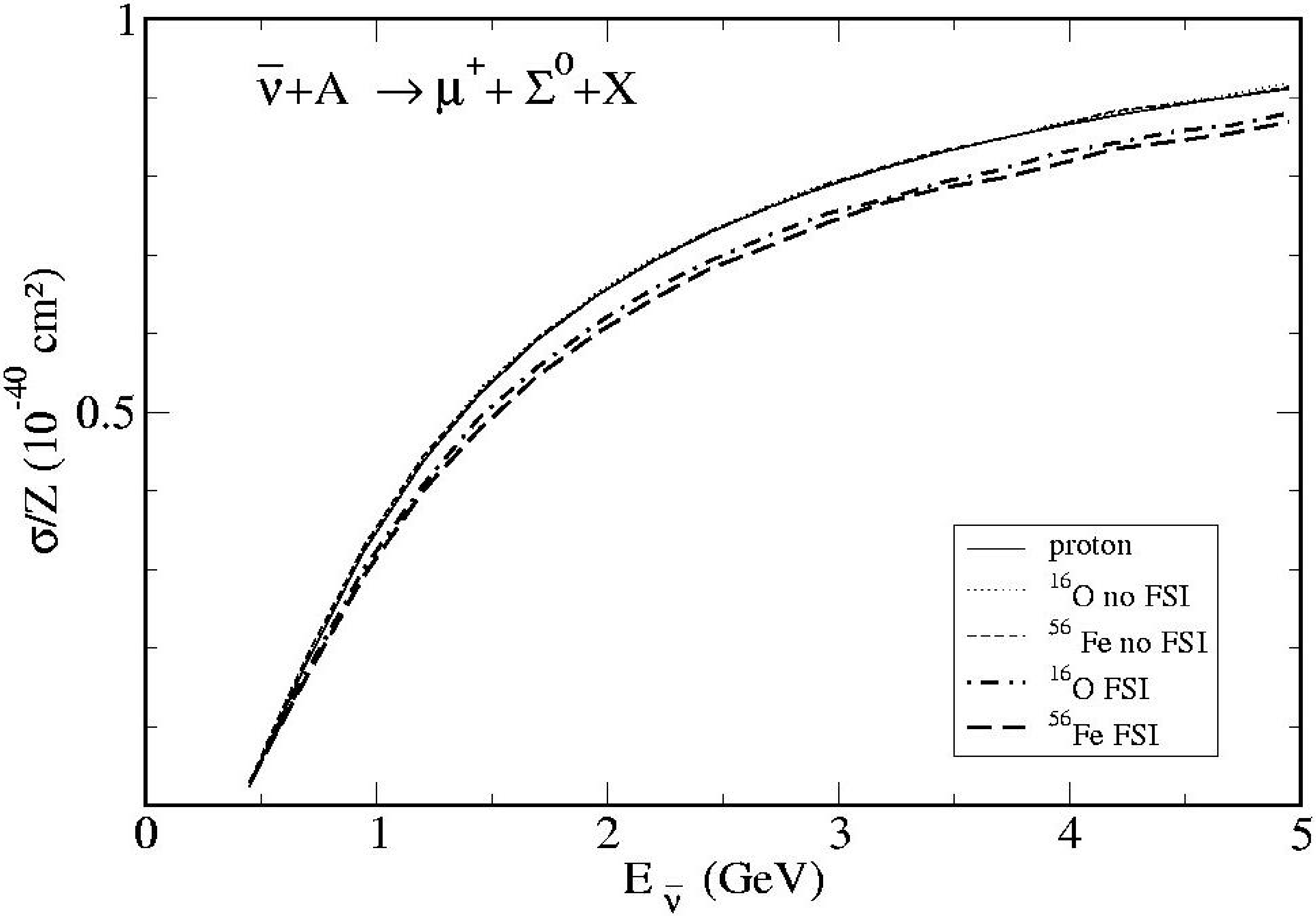
$$\mu_p = 1.792847 \quad , \mu_n = -1.913043$$

$$M_V = 0.84 \; GeV \quad , and \;\; \lambda_n = 5.6$$

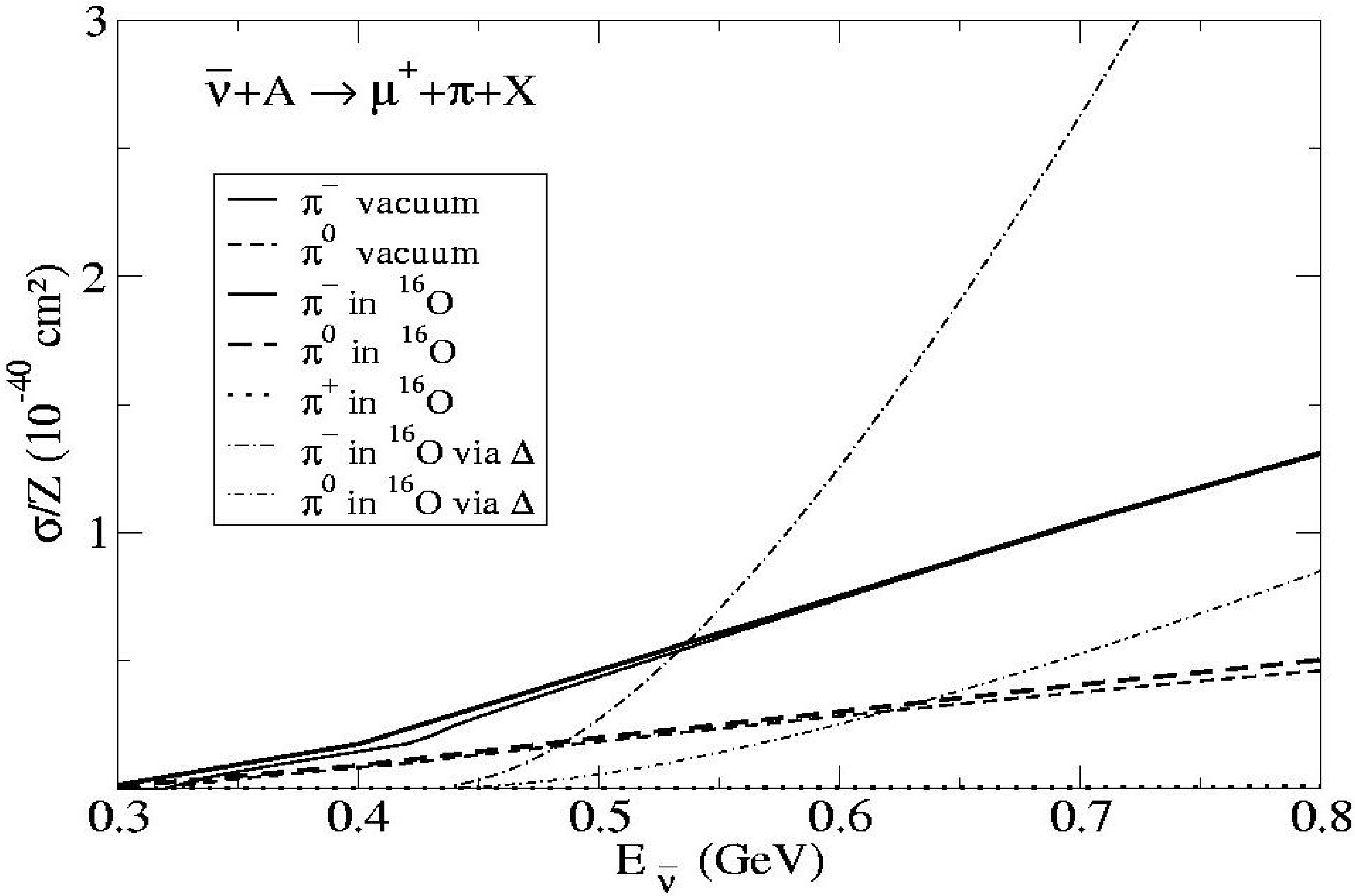


$\bar{\nu}+A \rightarrow \mu^{+}+\Lambda+X$
$\sigma/Z\ (10^{-40}\ cm^2)$
$E_{\bar{\nu}}$ (GeV)
0
1
2
3
4
5
proton
^{16}O no FSI
^{56}Fe no FSI
^{16}O FSI
^{56}Fe FSI


$\bar{\nu}+A \rightarrow \mu^{+}+\Sigma^{-}+X$
neutron
^{16}O no FSI
^{56}Fe no FSI
^{16}O FSI
^{56}Fe FSI
$\sigma/N\ (10^{-40}\ cm^2)$
$E_{\bar{\nu}}$ (GeV)
0
1
2
3
4
5



$\bar{\nu}+A \rightarrow \mu^{+}+\Sigma^{0}+X$
1
0.5
$\sigma/Z\ (10^{-40}\ cm^2)$
0
1
2
3
4
5
$E_{\bar{\nu}}$ (GeV)
proton
^{16}O no FSI
^{56} Fe no FSI
^{16}O FSI
^{56}Fe FSI



$\bar{\nu}+A \rightarrow \mu^{+}+\pi+X$
π^{-} vacuum
π^{0} vacuum
π^{-} in ^{16}O
π^{0} in ^{16}O
π^{+} in ^{16}O
π^{-} in ^{16}O via Δ
π^{0} in ^{16}O via Δ
σ/Z (10^{-40} cm^2)
$E_{\bar{\nu}}$ (GeV)
0.3
0.4
0.5
0.6
0.7
0.8
1
2
3

Conclusions

- Pion production is dominated by Incoherent processes.
- The effect of nuclear medium and final state interaction is large for Coherent production as compared to Incoherent production.
- The role of nuclear medium and pion absorption effects is quite important in bringing out the good agreement between the theoretical and experimental results in the energy region of 1GeV.
- The theoretical results for pion production from free nucleon are in good agreement with the older data from ANL, but are smaller than the older data from BNL.

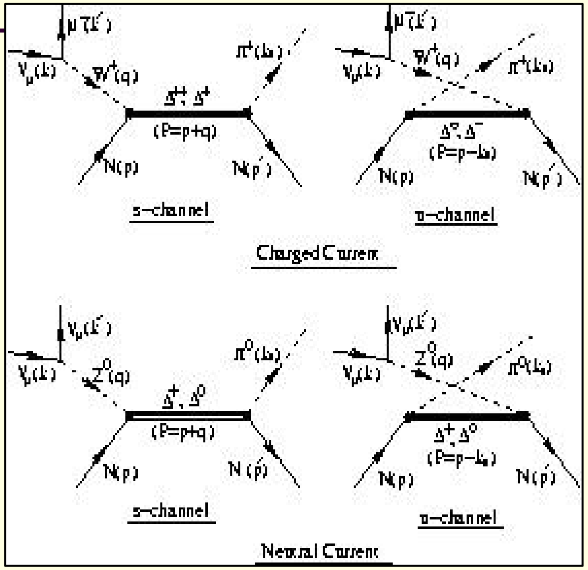
Conclusions

- The theoretical results for the pion production are in fair agreement with the recent experimental results from MiniBooNE Collaboration in the energy region of about 1GeV.
- The theoretical cross sections for coherent pion production are in fair agreement with the recent experimental results reported from K2K and MiniBooNE Collaborations.
- There is about 15-20% uncertainty in the total cross section due to form factors

Coherent Pion Production

We calculate the Coherent Pion Production induced by Charged and Neutral Current interactions

$$\nu_l(k) + {}^A_Z X(p) \rightarrow l^-(k') + {}^A_Z X(p') + \pi^+(k^\pi)$$



The calculations are done in Local Density Approximation (LDA) using Δ dominance

$$M = \frac{G}{\sqrt{2}} Cos\theta_c \left[\bar{u}(k')\gamma^\mu(1-\gamma^5)u(k)\right]\left[J^s_\mu F(\vec{q}-\vec{k}^\pi) + J^u_\mu F(\vec{q}-\vec{k}^\pi)\right]$$

$$J^s_\mu = \sqrt{3}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right) k^\pi_\sigma \sum_s \overline{\psi}^s(p')\Delta^{\sigma\lambda} O_{\lambda\mu}\psi^s(p)$$

$$J^u_\mu = \sqrt{3}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right) \sum_s \overline{\psi}^s k^\pi_\sigma(p') O^{\sigma\lambda}\Delta_{\lambda\mu}\psi^s(p)$$

Where $\Delta_{\alpha\beta}$ is the relativistic delta propagator

$$\Delta_{\alpha\beta} = \frac{\not{P} + M_\Delta}{P^2 - M^2_\Delta + i\Gamma M_\Delta}\left[g_{\alpha\beta} - \frac{1}{3}\gamma_\alpha\gamma_\beta - \frac{2}{3M^2_\Delta}P_\alpha P_\beta + \frac{1}{3M_\Delta}(P_\alpha\gamma_\beta - \gamma_\alpha P_\beta)\right]$$

$$\xi^{I=1}_V = \frac{1}{2Sin\theta_W Cos\theta_W}(1-2Sin^2\theta_W)$$

$$\xi^{I=1}_A = -\frac{1}{2Sin\theta_W Cos\theta_W}$$

$O^{\sigma\lambda}$ is the weak N-Δ transition vertex. For neutral current Its vector and axial part are multiplied by factors

Coherent charged current one π^- production process induced by anti ν_μ on ^{12}C target.

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