Importance of cross section in predicting the neutrino event rates

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27-06-2012

CONTENTS

Neutrino Event Rates

$$\text{Event} = \sigma \times \Phi \times T \times N_{Target}$$

σ Neutrino interaction cross section

Φ Neutrino flux

T Time of Exposure

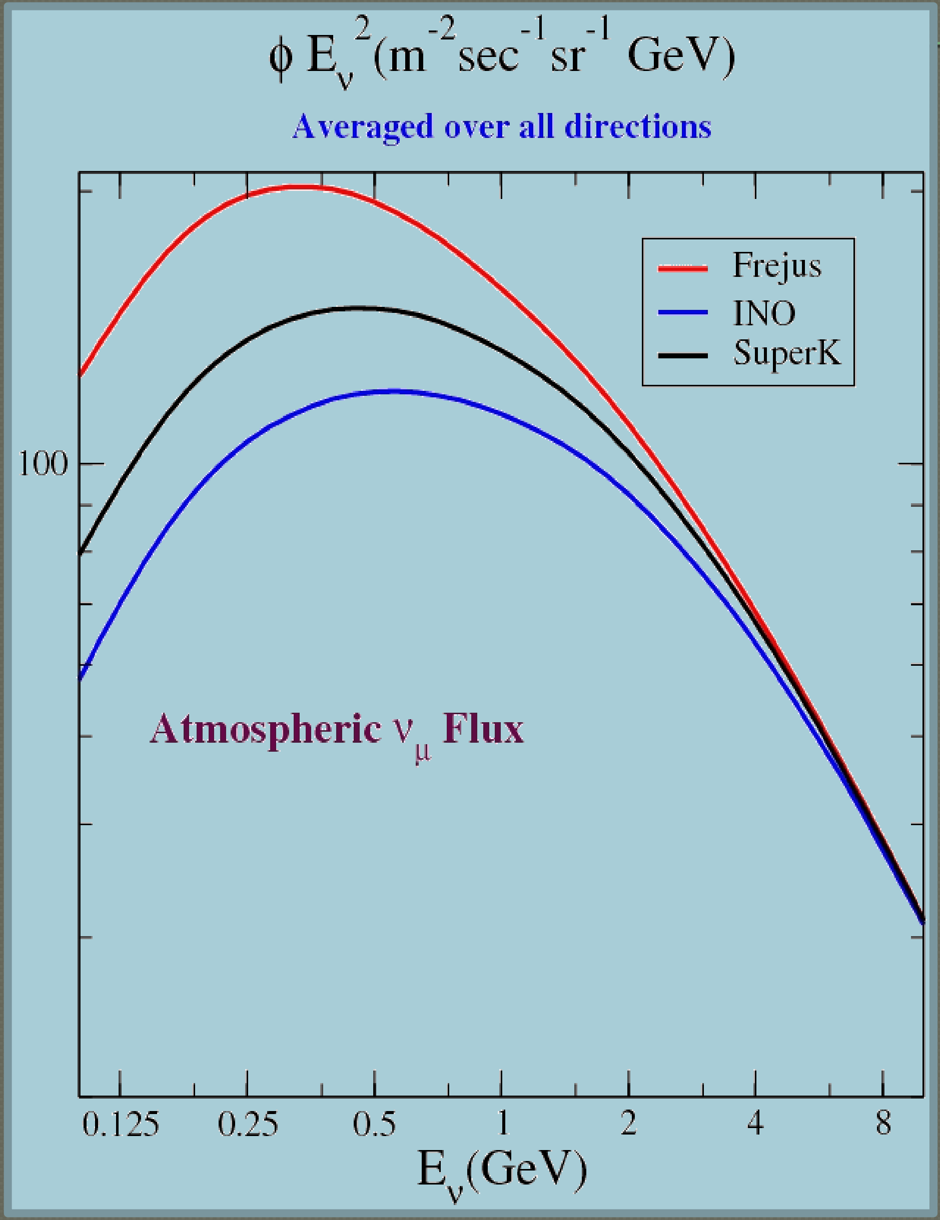
N_{Target} is the number of target particles

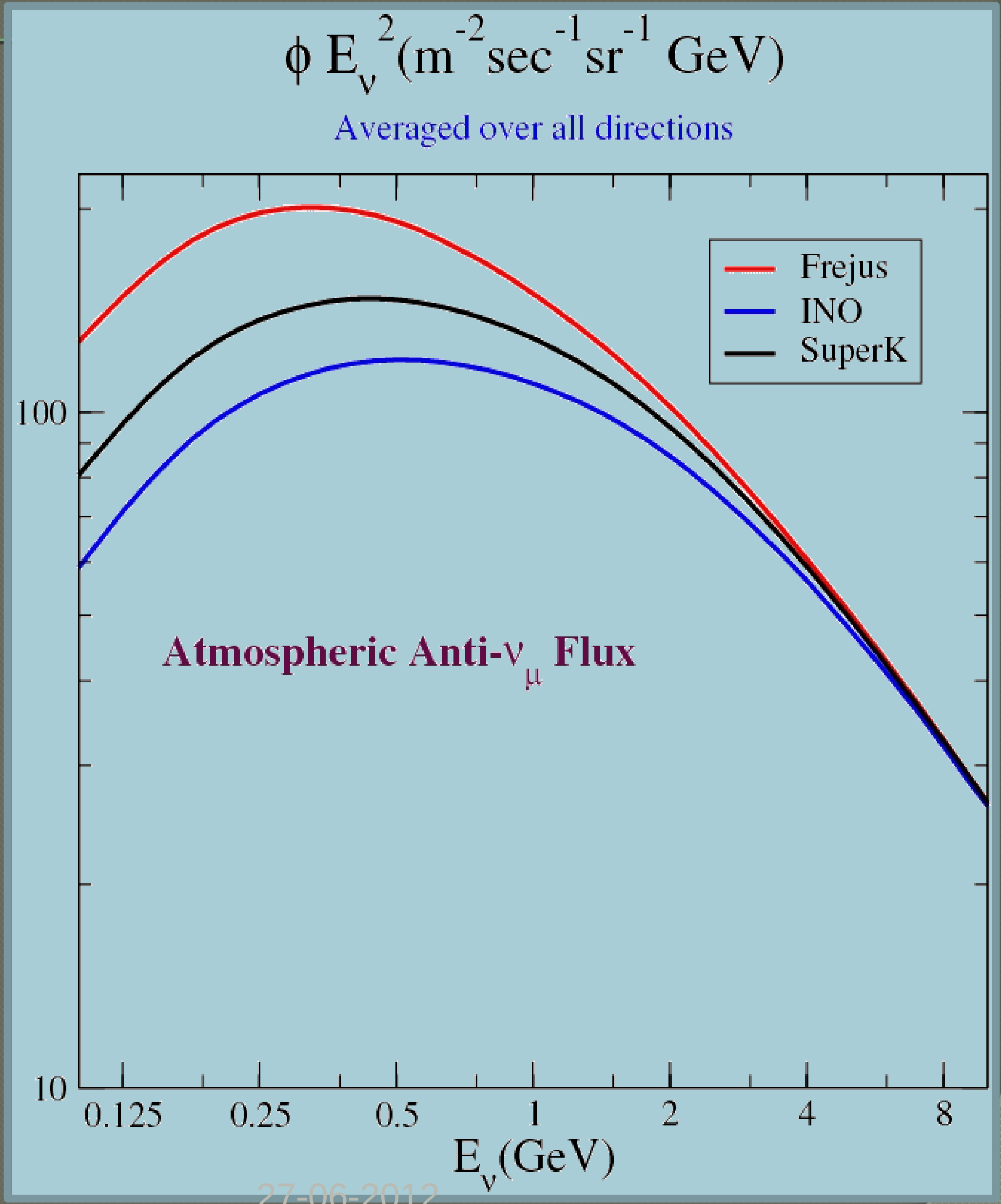
For example σ is around $10^{-44} cm^2$ for $\nu_e - e^-$ scattering.

$\Phi_\nu = 6.5 \times 10^6 / cm^2 / sec$ (Solar ν flux)

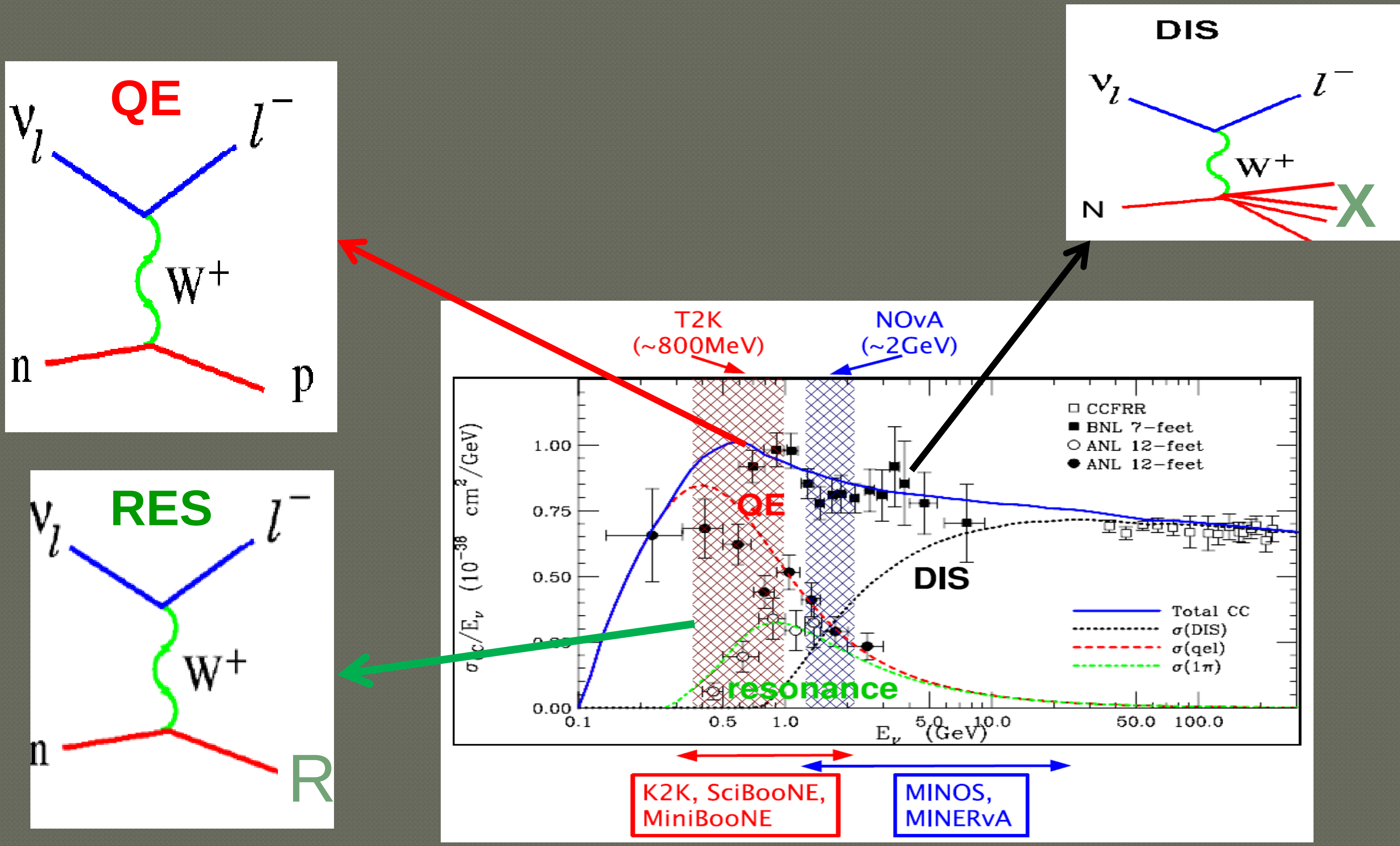
ATMOSPHERIC NEUTRINO FLUX

M. Honda





Most of the neutrino experiments are being performed in the few GeV energy region. In this energy region the contribution to the cross section comes from the quasielastic, inelastic and deep-inelastic processes.



QUASIELASTIC CHARGED CURRENT SCATTERING

Phys. Rev. C61 (2000) 028501

Eur. Phys. J. A24 (2005) 459

Phys. Lett. B 641 (2006) 159

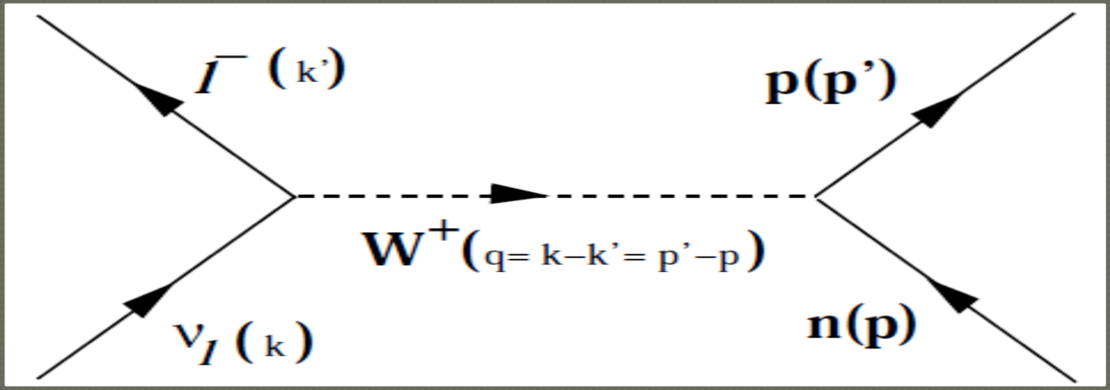
Eur. Phys. J. A 43 (2010) 209

J. Phys. G3 7 (2010) 015005

Quasielastic Charged Current Reaction

Basic ν_l - neutron reaction taking place in nucleus

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



Matrix element

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \cos\theta_C \; l_\mu \; J^\mu$$

where

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

Hadronic current

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

$F_1^V(q^2)$, $F_2^V(q^2)$, $F_A^V(q^2)$ and $F_P^V(q^2)$ are isovector form factors

$$F_{1,2}^V(q^2) = F_{1,2}^p(q^2) - F_{1,2}^n(q^2)$$

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

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

$F_1^V(0) = 1{\cdot}0$, $F_2^V(0) = 3{\cdot}7059$, Dipole mass $M_v = 0{\cdot}84$ GeV

$\mu_p = 1{\cdot}7928473\ \mu_N$, $\mu_n = -\,1{\cdot}9130427\ \mu_N$, $\lambda_n = 5{\cdot}6$

Isovector axial form factor

$$F_A(Q^2) = F_A(0)\ \left[1 + \frac{Q^2}{M_A^2}\right]^{-2}$$

and pseudoscalar form factor

$$F_p^V(Q^2) = \frac{2M F_A^V(Q^2)}{m_\pi^2 + Q^2}$$

Axial Charge $F_A(0) = -\,1{\cdot}26$ and axial dipole mass $M_A = 1{\cdot}1$ GeV

Different values of M_A

World Average Value - 1.026 ± 0.02 GeV

NOMAD - 1.05 ± 0.02 ± 0.06 GeV

K2K (SciBar detector) - 1.14 ± 0.11 GeV

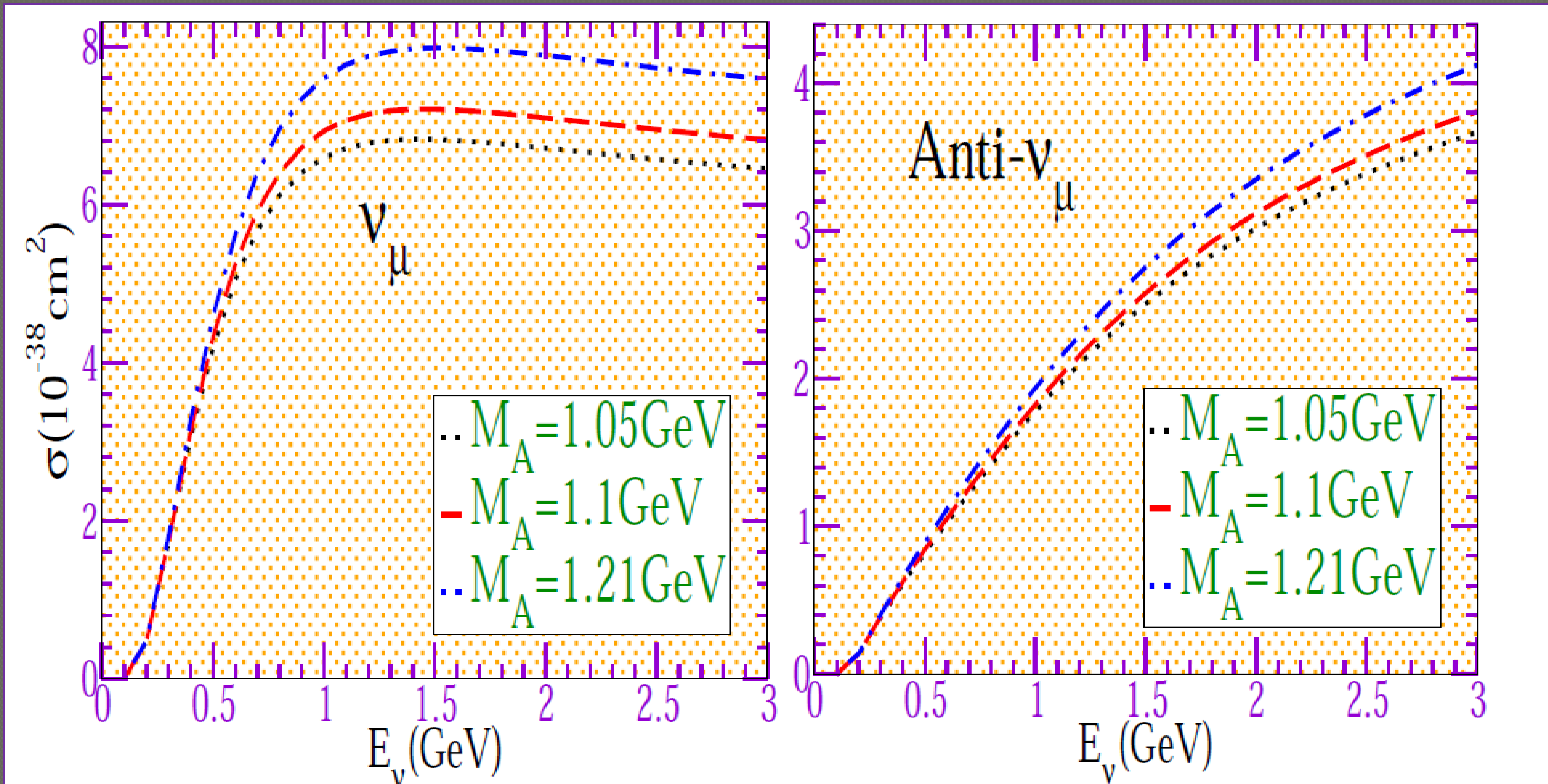
K2K (SciFi detector) - 1.20 ± 0.12 GeV

MiniBooNE experiment - 1.23 ± 0.2 GeV

MiniBooNE experiment - 1.35 ± 0.2 GeV

MINERvA experiment- 1.0GeV

Axial mass dependence on total cross section



- *σ increases by about 15 % when M_A is changed from 1·05 to 1·21 GeV for neutrino and by about 7- 8 % in the case of antineutrino at E_ν=1GeV*

The double differential cross section for the process

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

in the Lab frame is given by

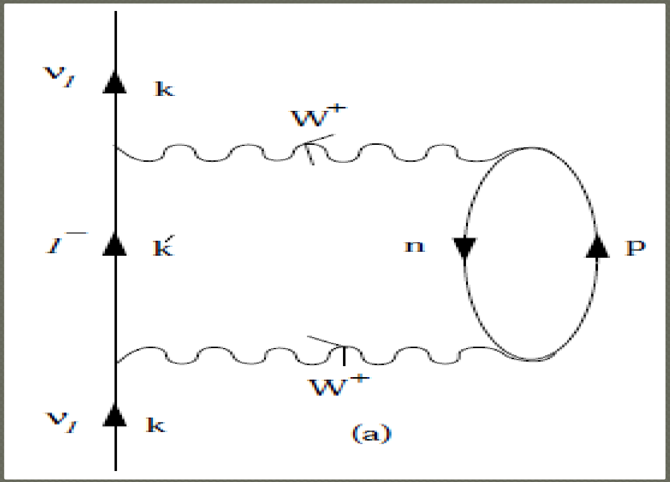
$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE_l'} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}L_{\mu\nu}J^{\mu\nu}$$

$$L_{\mu\nu} \;=\; L^s_{\mu\nu} + \mathrm{i}L^a_{\mu\nu} = k'_\mu k_\nu + k'_\nu k_\mu - g_{\mu\nu}k\cdot k' + \mathrm{i}\epsilon_{\mu\nu\alpha\beta}k'^\alpha k^\beta$$

$$W^{\mu\nu} = \frac{1}{2M_i}\overline{\sum_f}(2\pi)^3\delta^4(P'_f - P - q)\langle f|j^\mu_{\mathrm{cc}}(0)|i\rangle\langle f|j^\nu_{\mathrm{cc}}(0)|i\rangle^*$$

The hadronic tensor is determined by the $W^\pm$ boson self-energy $\Pi^{\mu\nu}_W(q)$, in the nuclear medium

First we evaluate the neutrino selfenergy, $\Sigma^{\lambda}_{\nu}(k;\rho)$ moving in the nuclear matter of density ρ



$$
\begin{aligned}
-i\Sigma^{\lambda}_{\nu}(k) \quad &= \quad \int \frac{d^4q}{(2\pi)^4}\ \bar{u}^{\lambda}_{\nu}(k)\left\{-\frac{ie}{\sqrt{2}sin\theta_w}\gamma_\mu\frac{1}{2}(1-\gamma_5)\right\} \\
&\times \quad \left\{\frac{i(\not{k}'+m_l)}{\not{k}'^{\ 2}-m_l^2+i\epsilon}\right\}\left\{-\frac{ie}{\sqrt{2}sin\theta_w}\gamma_\nu\frac{1}{2}(1-\gamma_5)\right\} \\
&\times \quad u^{\lambda}_{\nu}(k)\left(\frac{-i(g_{\mu\rho}-\frac{q_\mu q_\rho}{M_W^2})}{q^2-M_W^2}\right)(-i)\Pi^{\rho\sigma}(q)\left(\frac{-i(g_{\sigma\nu}-\frac{q_\sigma q_\nu}{M_W^2})}{q^2-M_W^2}\right)
\end{aligned}
$$

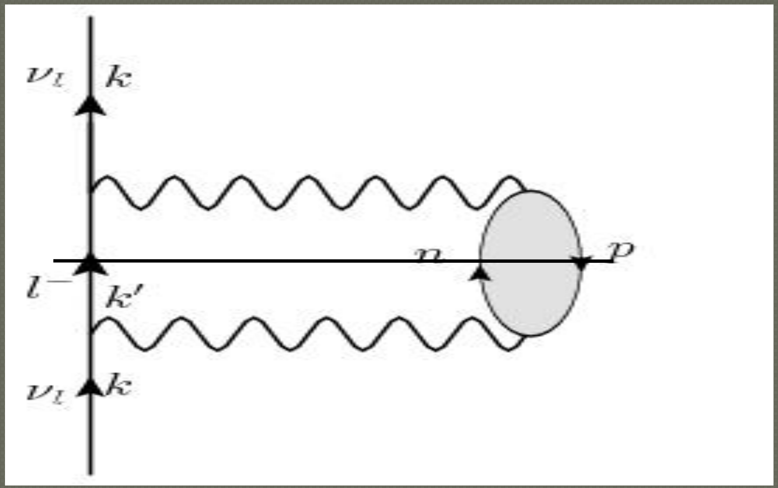
The sum over helicities leads to traces in the Dirac's space

$$\Sigma_\nu(k;\rho) = \frac{8\mathrm{i}G}{\sqrt{2}M_W^2}\int \frac{d^4q}{(2\pi)^4}\frac{L_{\mu\nu}\Pi_W^{\nu\mu}(q;\rho)}{k'^2 - m_l^2 + \mathrm{i}\epsilon}$$

The neutrino disappears from the elastic flux, by inducing 1p-1h, 2p-2h, Δ-h excitations or creating pions, etc…. at a rate given by

$$\Gamma(k;\rho) = -\frac{1}{E_\nu}\mathrm{Im}\Sigma_\nu(k;\rho)$$

We get the imaginary part of Σ_ν by using the cutkosky's rules



Those states are then placed on shell by taking the imaginary part of the propagator, self-energy, etc.

$$\mathrm{Im}\Sigma_\nu(k) = \frac{8G}{\sqrt{2}M_W^2}\int \frac{d^3k'}{(2\pi)^3}\frac{\Theta(q^0)}{2E'_l}\,\mathrm{Im}\left\{\Pi_W^{\mu\nu}(q;\rho)L_{\nu\mu}\right\}$$

$$\Gamma(k;\rho) = -\frac{1}{E_\nu}\mathrm{Im}\Sigma_\nu(k;\rho)$$

Γdtds provides a probability times a differential of area, which is a contribution to the (ν_l,l) cross section

$$d\sigma = \Gamma(k;\rho)dtdS = -\frac{1}{k^0}\mathrm{Im}\Sigma_\nu(k;\rho)dtdS = -\frac{1}{|\vec{k}|}\mathrm{Im}\Sigma_\nu(k;\rho)dV = -\frac{1}{|\vec{k}|}\mathrm{Im}\Sigma_\nu(k;\rho)d^3r$$

The nuclear cross section is given by

$$\sigma = -\frac{1}{|\vec{k}|}\int \mathrm{Im}\Sigma_\nu(k;\rho(r))d^3r$$

The differential scattering cross section

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dk'^0} = -\frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}\left(\frac{2\sqrt{2}}{g}\right)^2\int\frac{d^3r}{2\pi}\left\{L^s_{\mu\nu}\,\mathrm{Im}(\Pi^{\mu\nu}_W+\Pi^{\nu\mu}_W)-L^a_{\mu\nu}\,\mathrm{Re}(\Pi^{\mu\nu}_W-\Pi^{\nu\mu}_W)\right\}\Theta(q^0)$$

Which results the hadronic tensor as

$$W_s^{\mu\nu} = -\Theta(q^0)\left(\frac{2\sqrt{2}}{g}\right)^2\int\frac{d^3r}{2\pi}\,\mathrm{Im}\left[\Pi^{\mu\nu}_W+\Pi^{\nu\mu}_W\right](q;\rho)$$

$$W_a^{\mu\nu} = -\Theta(q^0)\left(\frac{2\sqrt{2}}{g}\right)^2\int\frac{d^3r}{2\pi}\,\mathrm{Re}\left[\Pi^{\mu\nu}_W-\Pi^{\nu\mu}_W\right](q;\rho)$$

when compared with

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE'_l} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}L_{\mu\nu}W^{\mu\nu}$$

Therefore, for 1p1h, one has

$$-\mathrm{i}\Pi_W^{\mu\nu}(q^0,\vec{q}) = -\cos^2\theta_C\left(\frac{g}{2\sqrt{2}}\right)^2\int\frac{d^4p}{(2\pi)^4}A^{\mu\nu}(p,q)G(p;\rho_n)G(p+q;\rho_p)$$

with the CC nucleon tensor given by

$$\begin{aligned} A^{\mu\nu}(p,q) &= Tr\left\{\left(2F_1^V\gamma^\mu - 2\mathrm{i}\mu_V\frac{F_2^V}{2M}\sigma^{\mu\alpha}q_\alpha - F_A\left(\gamma^\mu\gamma_5 - \frac{2M}{m_\pi^2-q^2}q^\mu\gamma_5\right)\right)(\not{p}+\not{q}+M)\right. \\ &\times \left.\left(2F_1^V\gamma^\nu + 2\mathrm{i}\mu_V\frac{F_2^V}{2M}\sigma^{\nu\beta}q_\beta - F_A\left(\gamma^\nu\gamma_5 + \frac{2M}{m_\pi^2-q^2}q^\nu\gamma_5\right)\right)(\not{p}+M)\right\} \end{aligned}$$

and

$$G(p\,;\rho) = \left(\frac{1}{p^2-M^2+\mathrm{i}\epsilon} + \frac{2\pi\mathrm{i}}{2E(\vec{p})}\delta(p^0-E(\vec{p}))\Theta(k_F-|\vec{p}\,|)\right)$$

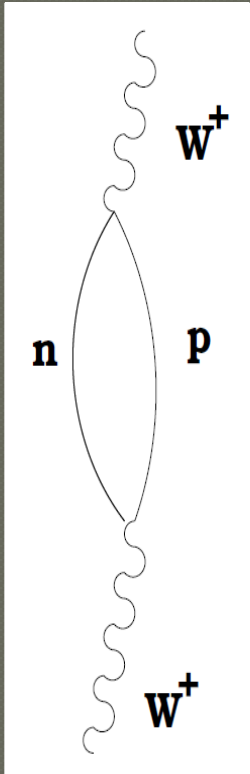
The expression for the hadronic tensor

$$W^{\mu\nu}(q^0,\vec{q}) = -\frac{\cos^2\theta_C}{2M^2}\int_0^\infty dr\ \ r^2\ \left\{2\Theta(q^0)\int\frac{d^3p}{(2\pi)^3}\frac{M}{E(\vec{p})}\frac{M}{E(\vec{p}+\vec{q})}\Theta(k_F^n(r)-|\vec{p}\,|)\Theta(|\vec{p}+\vec{q}\,|-k_F^p(r))\right.$$
$$\left.\times\ \ (-\pi)\delta(q^0+E(\vec{p})-E(\vec{p}+\vec{q}\,))A^{\nu\mu}(p,q)|_{p^0=E(\vec{p})}\right\}$$

The d^3p integrations above can be analytically done. This is done by taking the imaginary part of the Lindhard function, $\overline{U}_R(q,k_F^n,k_F^p)$

$$\int \frac{d\mathrm{p}}{(2\pi)^3} n_n(\mathrm{p},\mathrm{r}) \frac{M_n M_p}{E_n E_p} \delta[q_0 + E_n - E_p] \quad \rightarrow \quad -(1/\pi)\mathrm{Im}U_N(q_0,\vec{q})$$

Lindhard function corresponding to the p-h excitation



$$U_N(q_0,\vec{q}) = \int \frac{d\mathrm{p}}{(2\pi)^3} \frac{M_n M_p}{E_n E_p} \frac{n_n(p)\,[1 - n_p(\vec{p}+\vec{q})]}{q_0 + E_n(p) - E_p(\vec{p}+\vec{q}) + i\epsilon}$$

The imaginary part of the Lindhard function is obtained by using the relation

$$\frac{1}{\omega \pm i\eta} = \mathcal{P}\left(\frac{1}{\omega}\right) \mp i\pi\delta(\omega)$$

With these nuclear effects

$$\sigma(E_\nu) = -2{G_F}^2 cos^2\theta_c \int_{r_{min}}^{r_{max}} r^2 dr \int_{k'^{min}}^{k'^{max}} k' dk' \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{1}{E^2_{\nu_l} E_l} L^{(\nu)}_{\mu\nu} J^{\mu\nu} Im U_N[E_{\nu_l} - E_l - Q_r, \vec{q}]$$

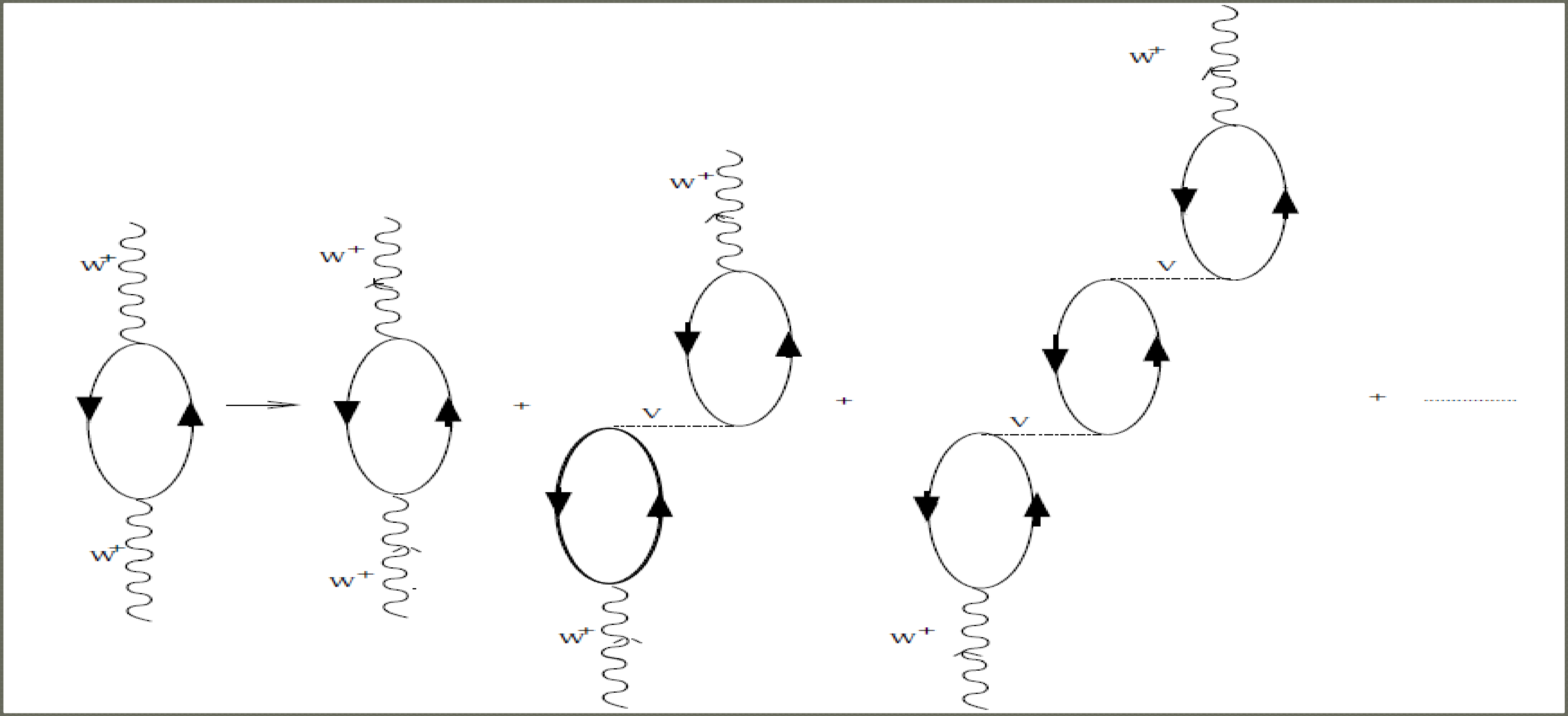
Due to Coulomb interaction, energy & momentum of outgoing lepton gets modified which has been taken into account in an effective momentum approximation.

Effective energy of the lepton in the coulomb field of the final nucleus

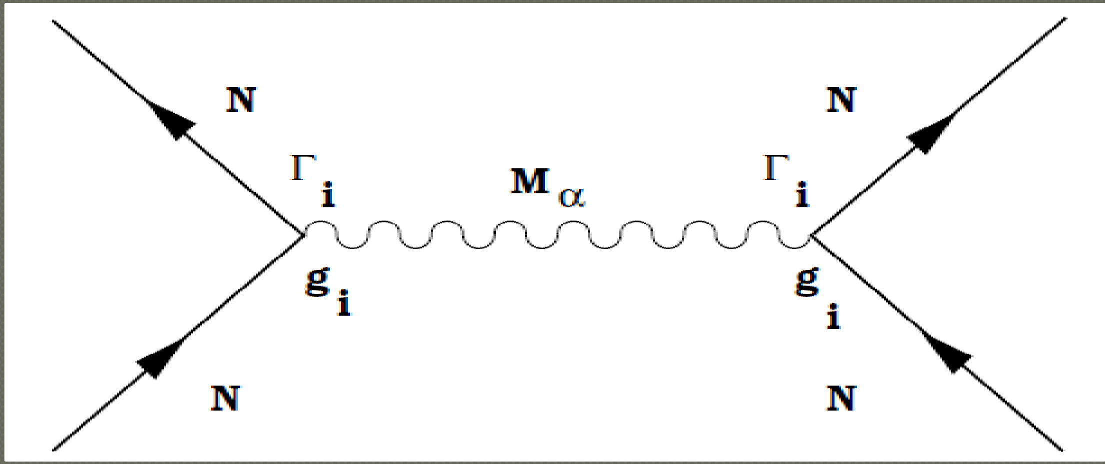
$$E_{eff} = E_l + V_c(r)$$

Random Phase Approximation (RPA)

In the nucleus there are many nucleons which strongly interacts among themselves resulting in a modification of the coupling strength as compared to the free ν-N coupling strength.



Generally N-N interaction is described by one boson exchange model



For π exchange (interaction with a pseudoscalar field

$$\mathcal{L}_{ps} = g_{ps}\overline{\psi} i\gamma_5 \psi \phi_{ps}$$

and for ρ exchange (interaction with a vector field

$$\mathcal{L}_v = g_v \overline{\psi}\gamma_\mu \psi \phi_v^\nu$$

These changes are calculated by considering the interaction of p-h excitations in the nuclear medium in Random phase approximation (RPA)

The N-N interaction for the RPA correlations in the nuclear medium results in the form of geometric series.

Due to this the Lindhard function modifies to

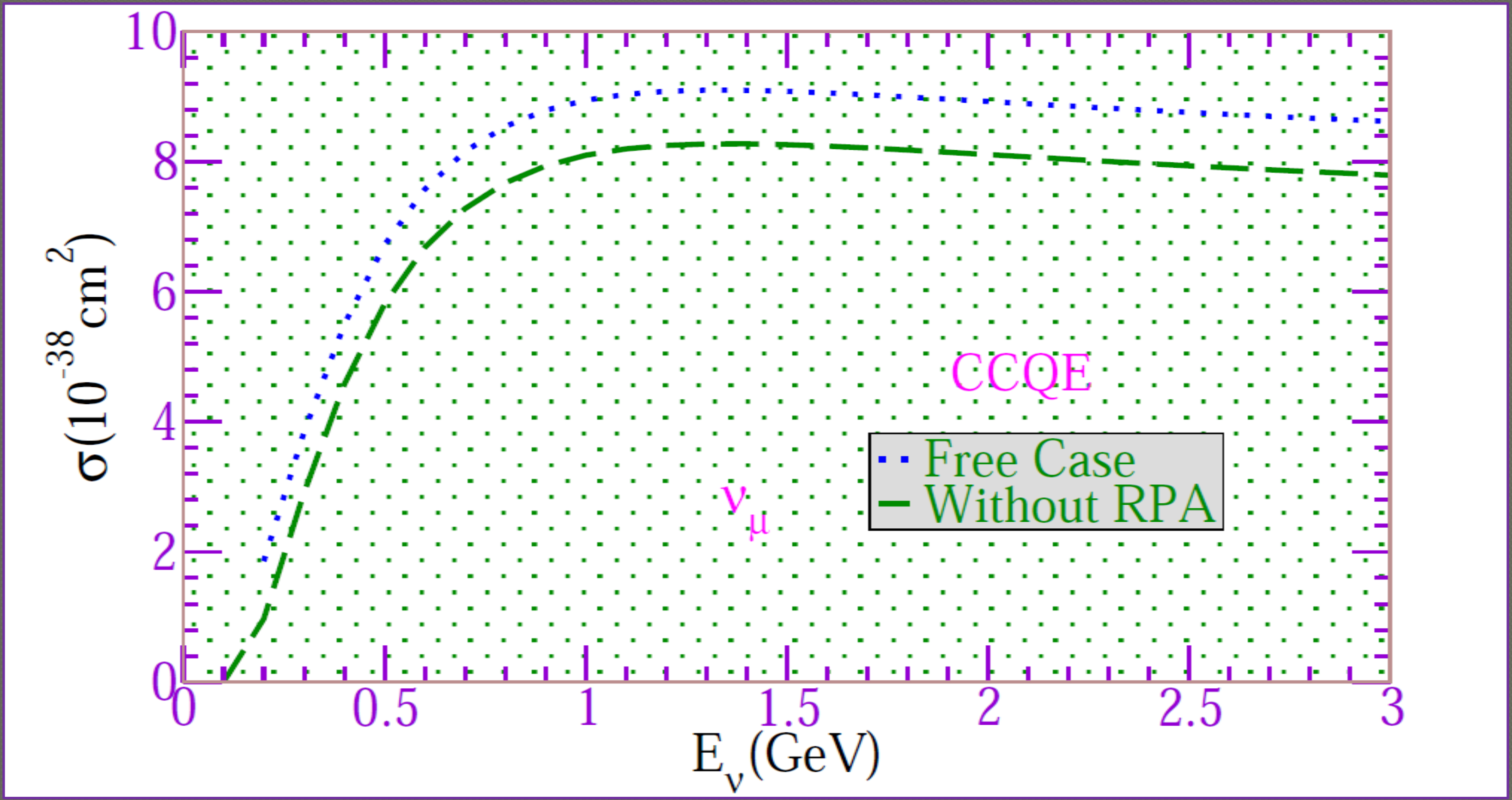
$$\overline{U}(q) = [U(q) + U(q)V_{ij}(q)\sigma_i\sigma_j U(q) + U(q)V_{ik}(q)\sigma_i\sigma_k U(q) \sigma_k\sigma_j V_{kj}(q)U(q) + \cdots\cdot]\tau_1 \cdot \tau_2$$

$$V_{ij} = V_l \widehat{q}_i \widehat{q}_j + V_t(\delta_{ij} - \widehat{q}_i\widehat{q}_j)$$

In the presence of nuclear medium effect, the total scattering cross section $\sigma(E_\nu)$

$$\sigma(E_\nu) = -2{G_F}^2 \cos^2\theta_c \int_{r_{min}}^{r_{max}} r^2 dr \int_{k'^{min}}^{k'^{max}} k' dk' \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{1}{E^2_{\nu_l} E_l} \times L^{(\nu)}_{\mu\nu} J^{\mu\nu}_{RPA} Im U_N [E_{\nu_l} - E_l - Q_r - V_c(r), \vec{q}]$$

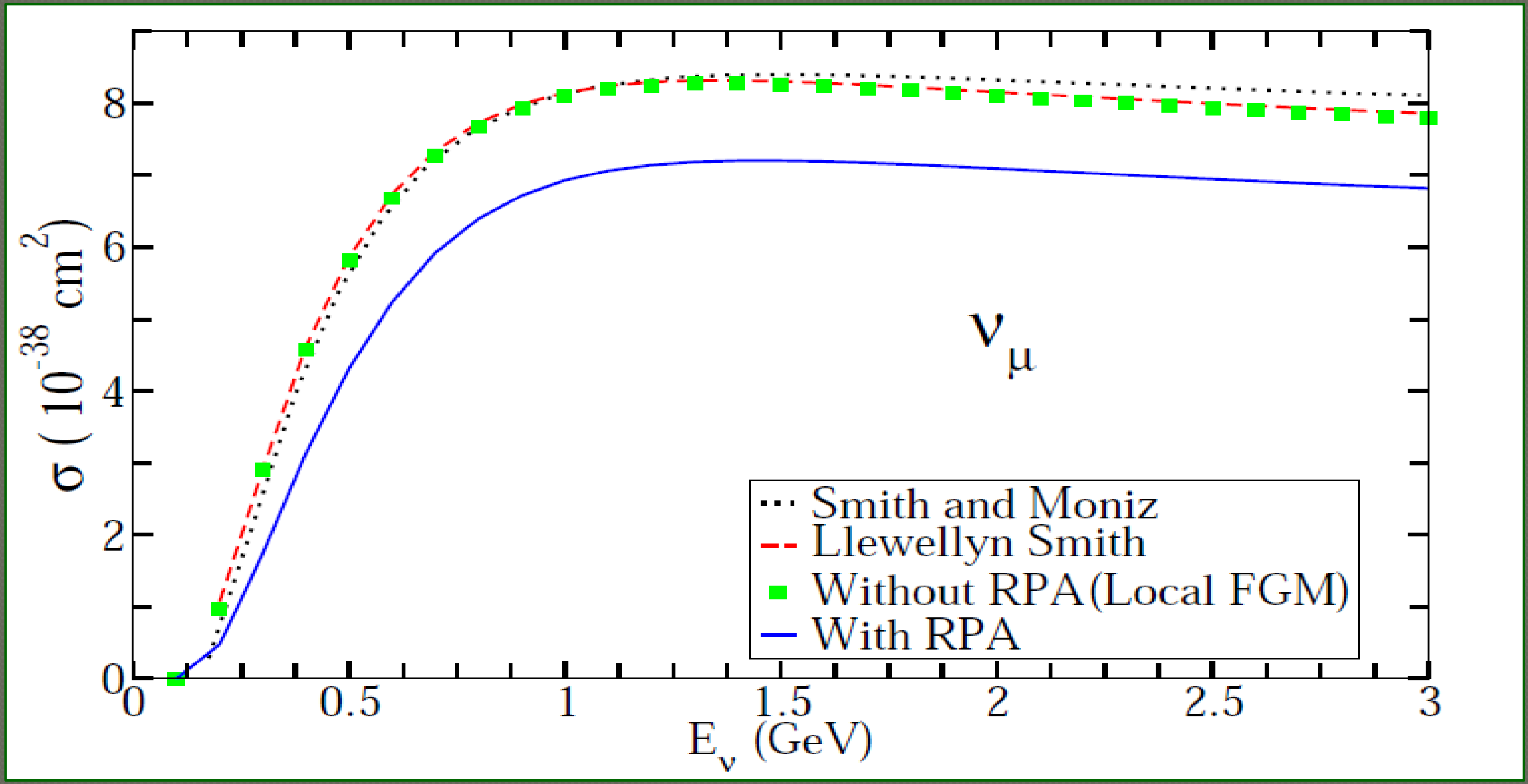
Total cross section for ν_μ induced quasielastic process



% reduction in the cross section

E_ν (GeV)	Free Case to Without RPA
0.4	18
1.0	10

Comparison of our local Fermi gas model (FGM) with other versions of Fermi gas model



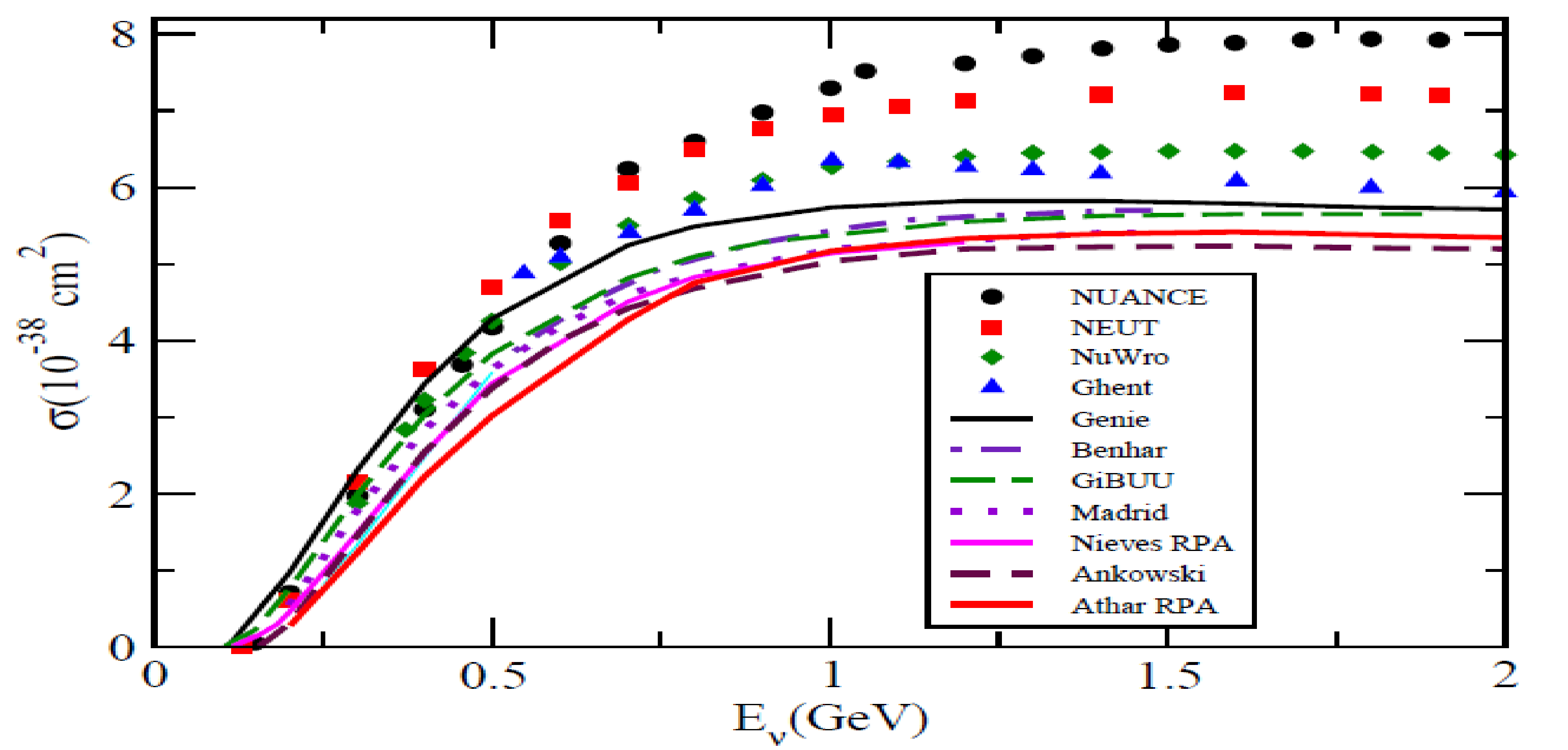
% reduction in the cross section

E_ν (GeV)	Without RPA to With RPA
0.4	30
1.0	15

EPJA 43 (2010) 209

Total Scattering cross section for CCQE process in ^{12}C

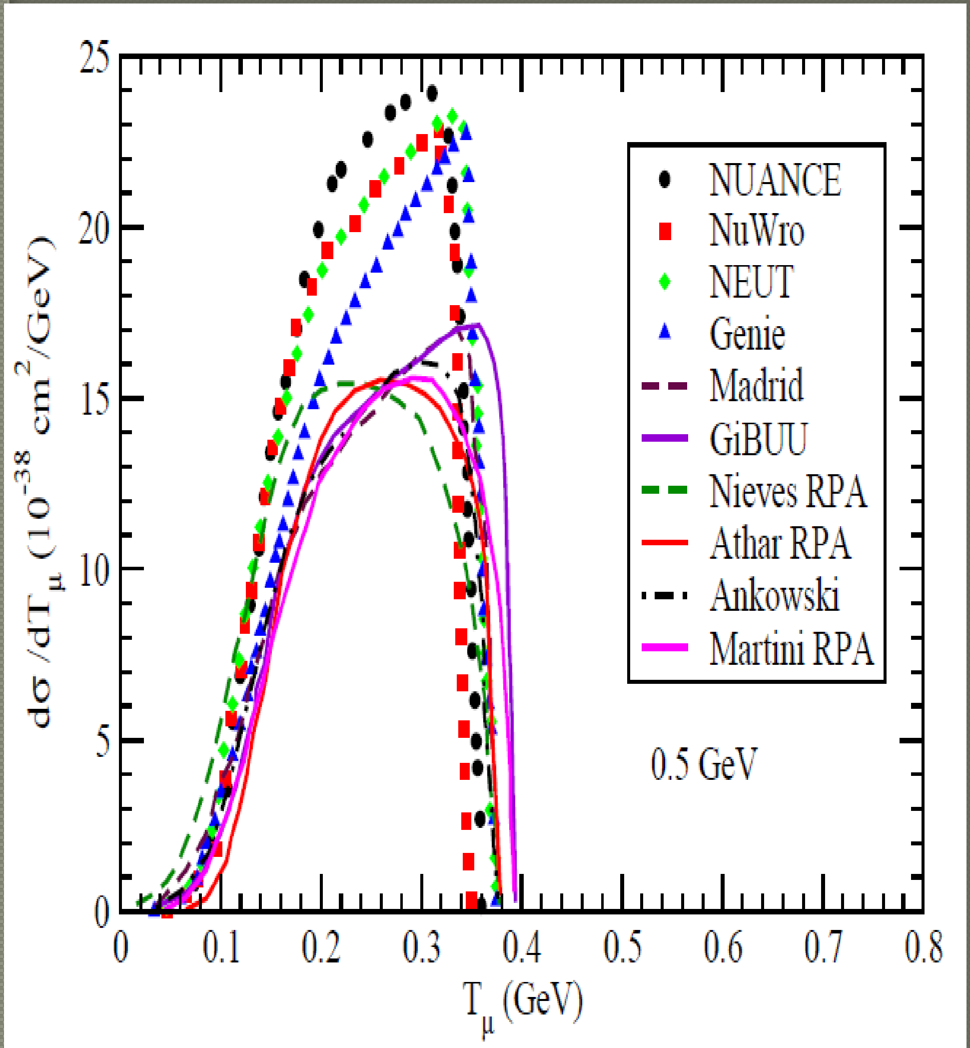
AIP Conf. Proc., 1189, 60 (2009)

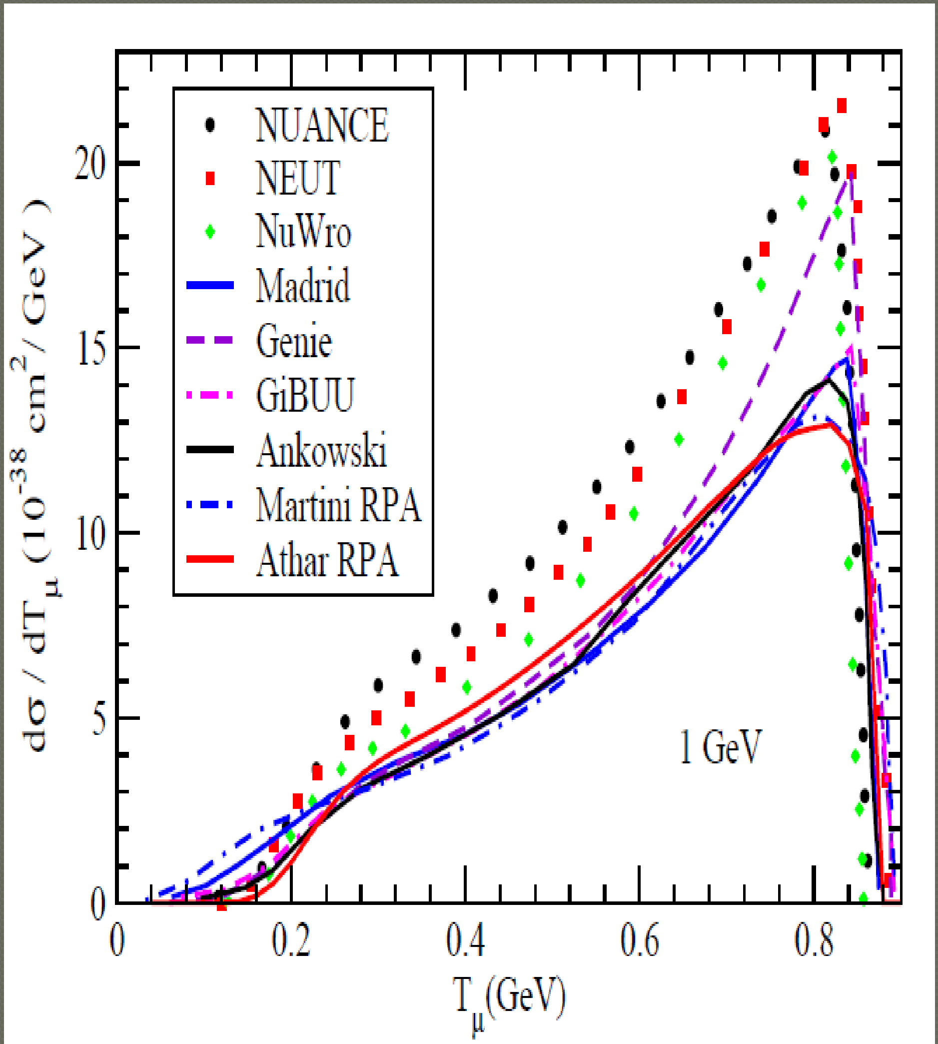


NUANCE : NP(PS) 112, 161 (2002); NEUT : NPA 484, 577 (1998); NuWro : PRC 74, 054316 920060; GHENT : PRC 79, 044603 (2009); GENIE : arXiv:hep-ph/0905.2517; Benhar : NPA 789, 379 (2007); GiBUU : PRC 73, 065502 (2006); Madrid : PRC 68, 048501 (2003); Nieves : PRC 73, 025501 (2006); Martini : arXiv: nucl-th/0909.0642; Ankowski : PRD 74, 054316 (2006); Athar RPA : PRD 74, 073008 (2006).

Differential cross section in the muon kinetic energy for ν_μ induced CCQE process in ^{12}C

AIP Conf. Proc., 1189, 60 (2009)

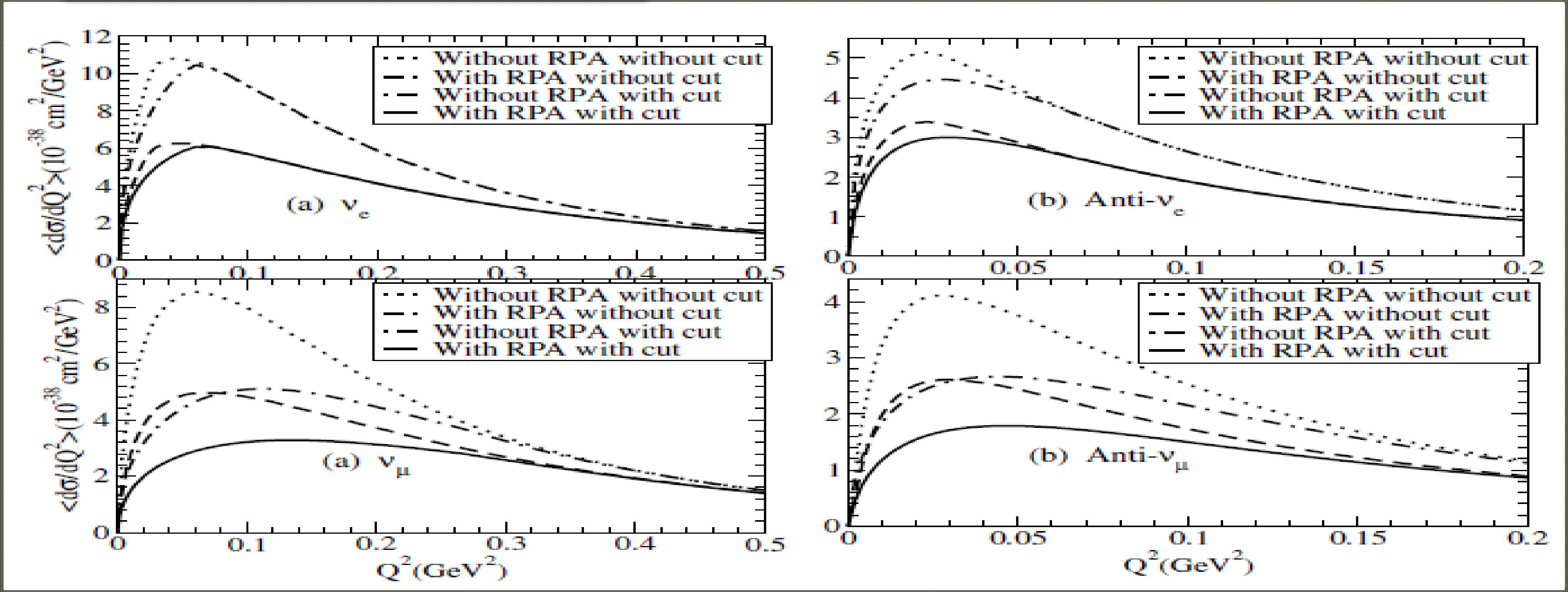




Differential cross sections averaged over atmospheric neutrino flux

Quasielastic process

EPJA, 43 209 (2010)



% reduction in the distribution

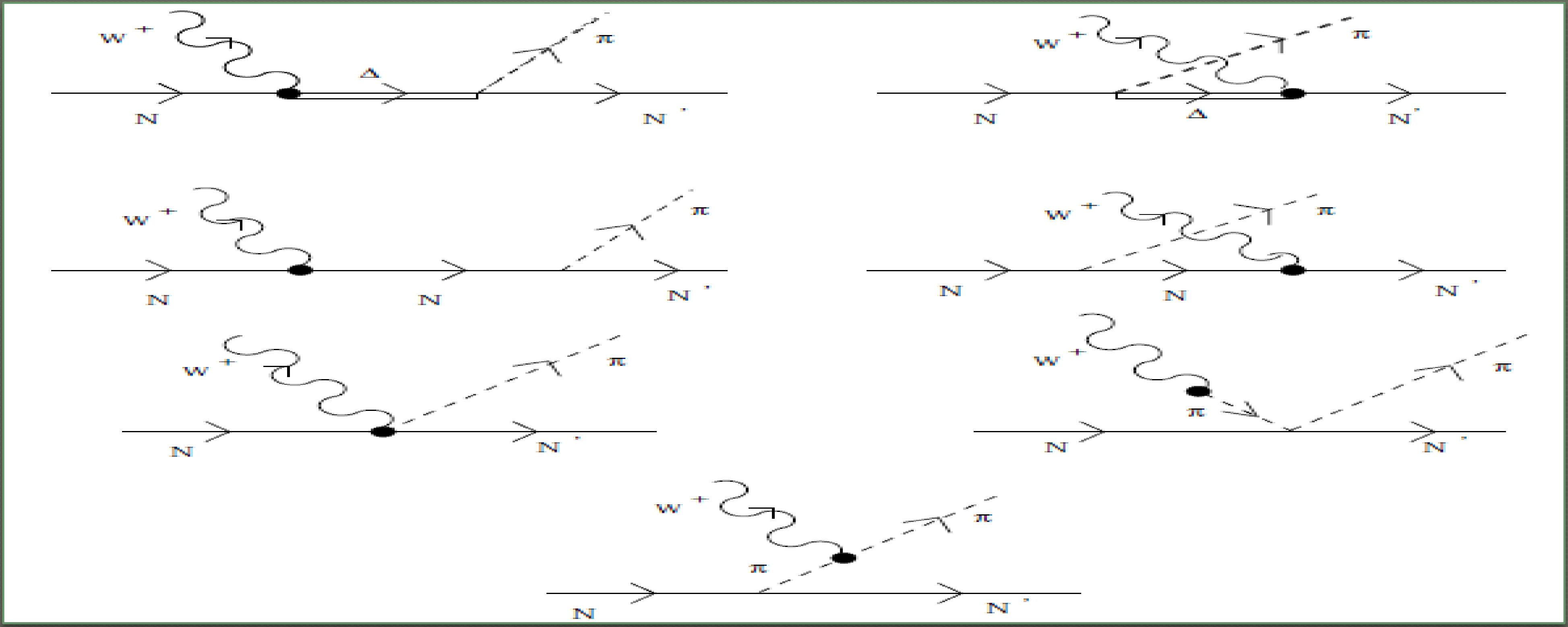
$Q^2\ (GeV^2)$	With RPA(without cut)	With RPA(With cut)
0.06	40	35
0.2	30	30

Inelastic pion production

Inelastic pion production

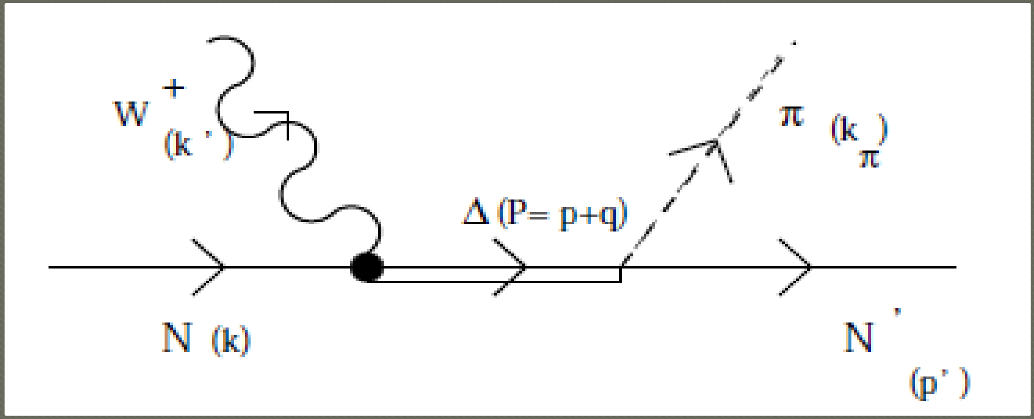
In the neutrino energy region below few GeV, the major contribution to the lepton event rates would come from the pions produced by the Δ excitation of the nucleon which subsequently decays into a nucleon and a pion.

Contribution for the one pion production process



Incoherent Process

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



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

Hadronic current $$J^\mu = \sqrt{3}\bar{\Psi}_\alpha \mathcal{O}^{\lambda\mu} u(p)$$

Matrix Element $$M_{fi} = \sqrt{3}\frac{G_F cos\theta_c}{\sqrt{2}}\frac{f_{\pi N\Delta}}{m_\pi}\bar{u}(\mathrm{p}')k_\pi^\sigma \mathcal{P}_{\sigma\lambda}\mathcal{O}^{\lambda\mu} l_\mu u(\mathrm{p})$$

$\mathcal{O}^{\lambda\mu}$ is the N – Δ transitions operators which is equal to the sum of vector and axial vector part

$$\mathcal{O}_V^{\lambda\mu} = \left(\frac{C_3^V(q^2)}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V(q^2)}{M^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V(q^2)}{M^2} \times (g^{\alpha\mu}q\cdot p - q^\alpha p^\mu) + \frac{C_6^V(q^2)}{M^2}q^\alpha q^\mu\right)\gamma_5$$

$$\mathcal{O}_A^{\lambda\mu} = \left(\frac{C_3^A(q^2)}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A(q^2)}{M^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + C_5^A(q^2)g^{\alpha\mu} + \frac{C_6^A(q^2)}{M^2}q^\alpha q^\mu\right)$$

Parameterization for the N – Δ transitions form factors

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

$$C_i^V(Q^2) = C_i^V(0)\left(1+\frac{Q^2}{M_V^2}\right)^{-2} \mathcal{D}_i \;, \quad i = 3,4,5.$$

where

$$\mathcal{D}_i = \left(1+\frac{Q^2}{4M_V^2}\right)^{-1} \quad \text{for} \quad i = 3,4 \quad and$$

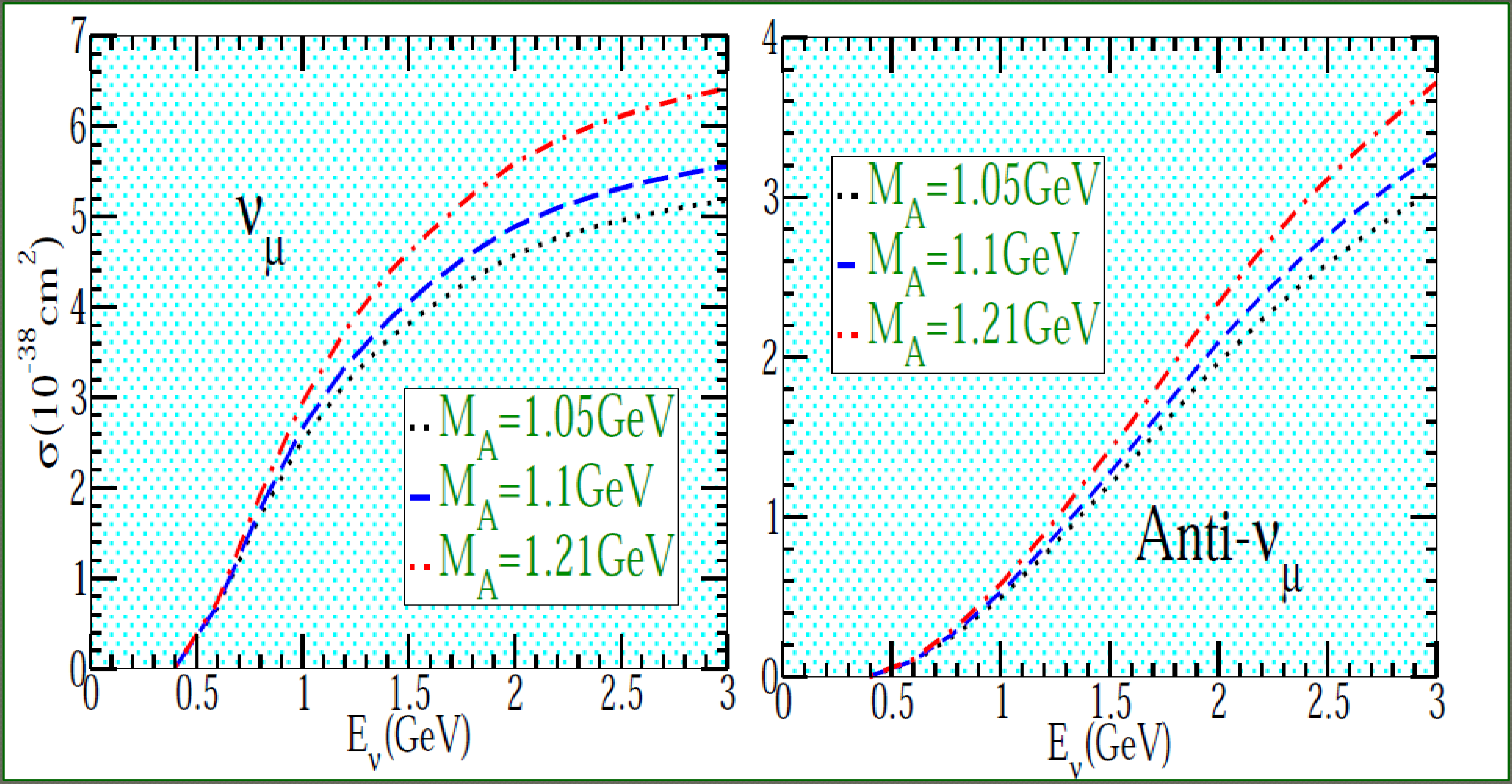
$$\mathcal{D}_i = \left(1+\frac{Q^2}{0.776M_V^2}\right)^{-1} \quad \text{for} \quad i = 5.$$

Axial vector form factor

$$C_i^A(Q^2) = C_i^A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}\left(1+\frac{Q^2}{3M_A^2}\right)^{-1}, \quad i = 3,4,5$$

$C_3^V(0) = 2.13$, $C_4^V(0) = -1.51$, $C_5^V(0) = 0.48$, $C_5^A(0) = 1.2$, M_V is the vector dipole mass, M_A is the axial dipole mass.

Axial mass dependence on total cross sections



σ increases by about 15 % when M_A is changed from 1.05 to 1.21 GeV for neutrino and by about 7-8 % in the case of antineutrino at E_ν = 1GeV

- In the nuclear medium delta decay mainly through the $\Delta \rightarrow N \pi$ channel. The momenta of 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

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

- In the nuclear medium there are additional decay channels open due to two body and three body absorption processes like $\Delta N \rightarrow NN$ and $\Delta NN \rightarrow NNN$ through which Δ disappear in the nuclear medium without producing a pion while a two body Δ absorption process like $\Delta N \rightarrow \pi NN$ gives rise to some more pions.

These nuclear medium effect on the Δ propagation are included by describing the mass and the decay width in terms of the self energy of $\Delta(\Sigma_\Delta)$.

Due to these changes Ѓ and M_Δ modify

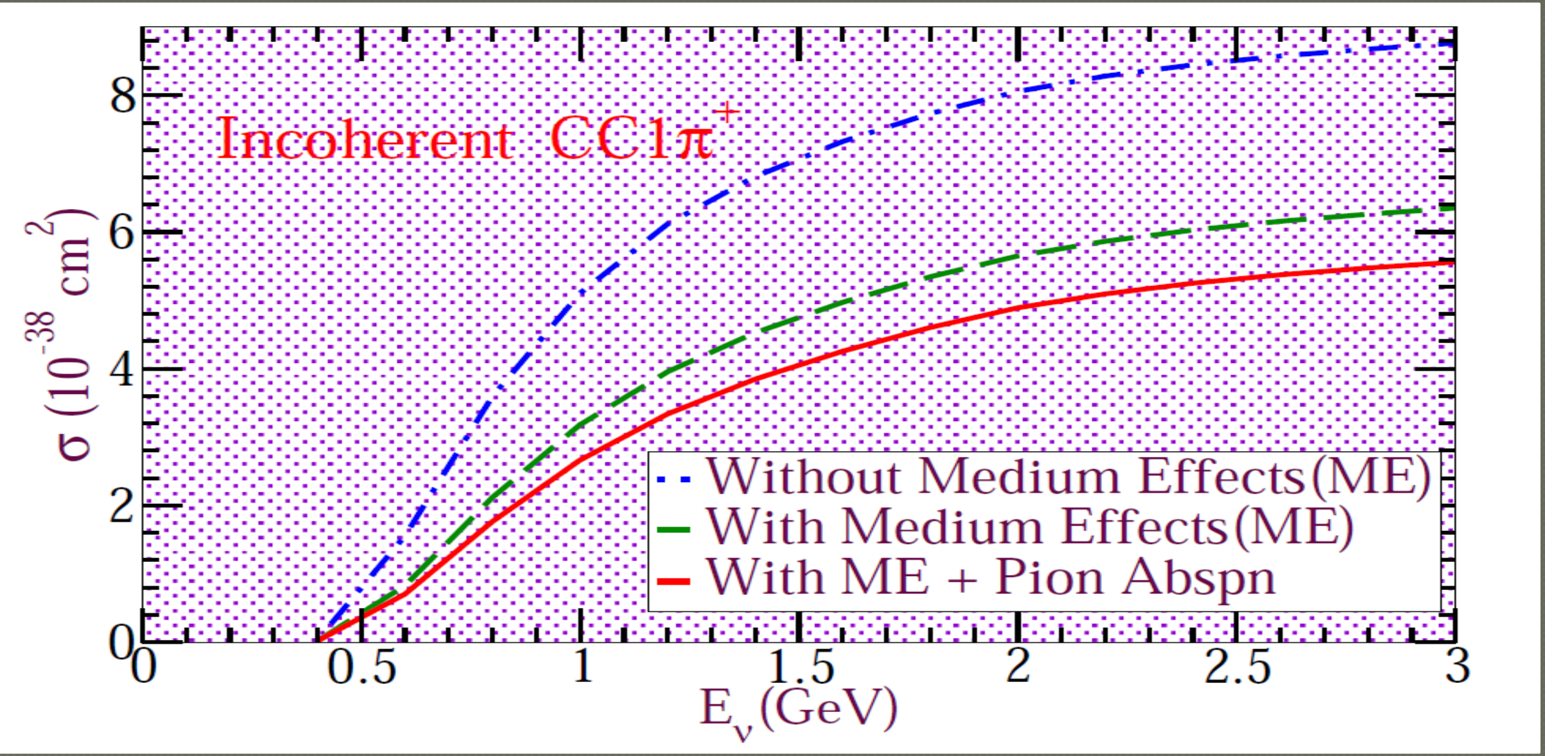
$$\frac{\tilde{\Gamma}}{2} \to \frac{\tilde{\Gamma}}{2} - Im\Sigma_\Delta \;\&\; \tilde{M}_\Delta \to M_\Delta + Re\Sigma_\Delta$$

E.Oset and L.L.Salcedo, Nucl. Phys. A468 631 (1987);
C.Garcia Recio, E.Oset, L.L.Salcedo, .. Nucl. Phys. A 526 685 (1991).

Final state interaction effects of pions is also taken into account by using Monte Carlo simulation code given by Vicente Vacas [Private Communication].

Total cross section for ν_μ induced incoherent $CC1\pi^+$ production process

IJMPE 18, 1469 (2009)

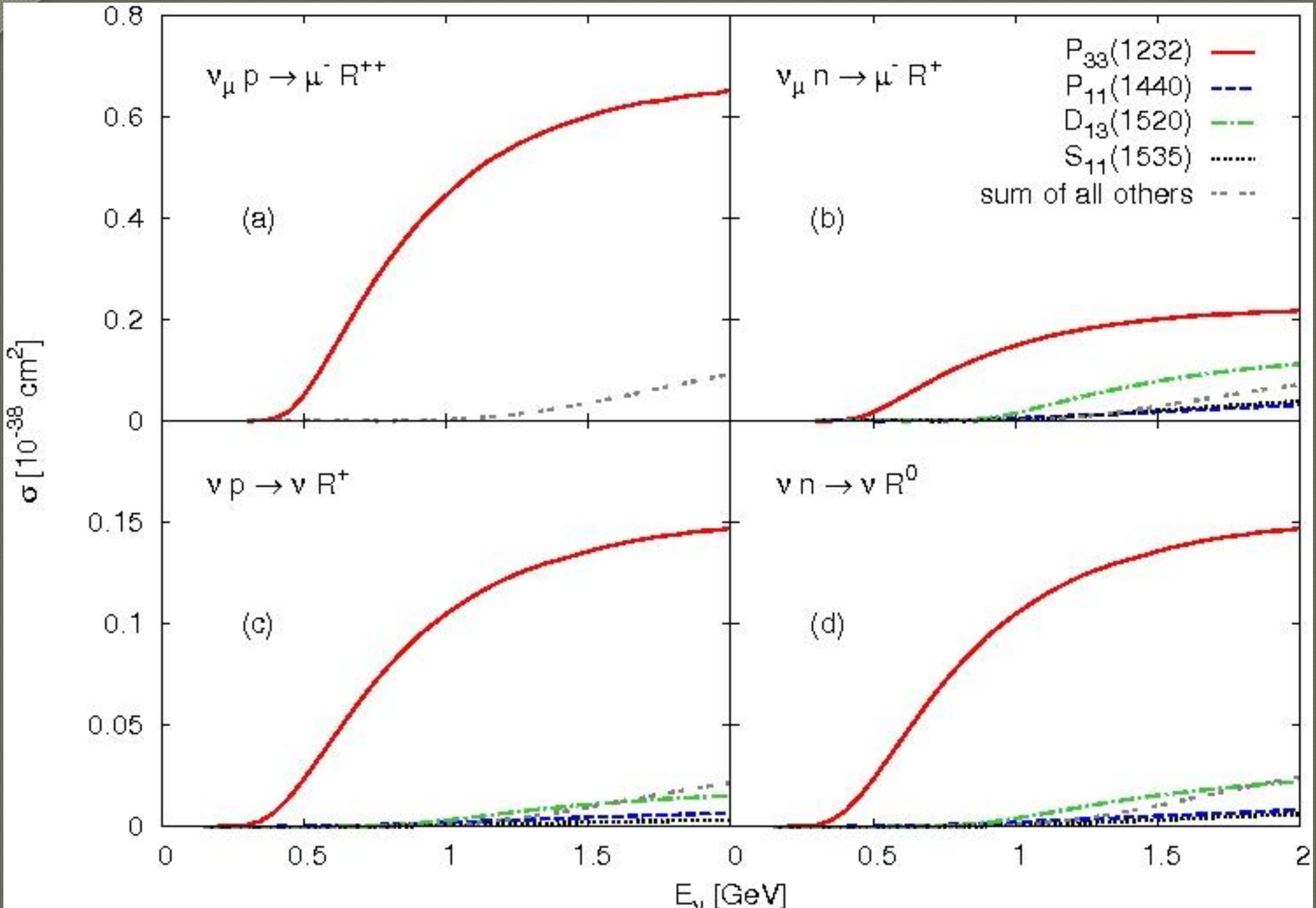


% reduction in the cross section

E_ν (GeV)	Without ME to With ME	With ME to With ME + Pion Abspn
0.4	40	15
1.5	30	15
3.0	28	12

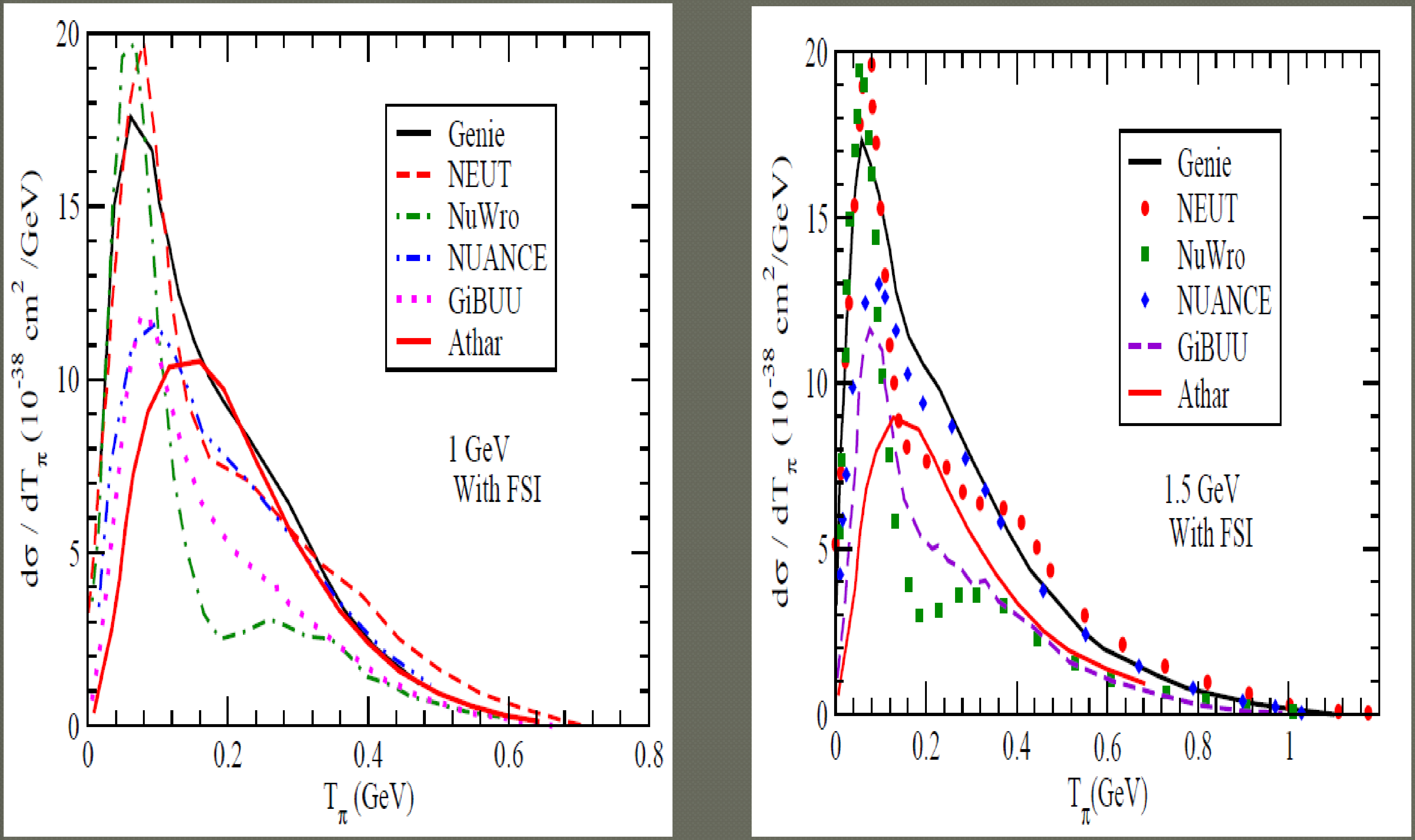
Resonances	M_R(GeV)	J	I	P	$\Gamma_0^{tot}(GeV)$
$P_{33}(1232)$	1.232	3/2	3/2	+	0.118
$P_{11}(1440)$	1.462	1/2	1/2	+	0.391
$D_{13}(1520)$	1.524	3/2	1/2	-	0.124
$S_{11}(1535)$	1.534	1/2	1/2	-	0.151
$S_{31}(1620)$	1.672	1/2	3/2	-	0.154
$S_{11}(1650)$	1.659	1/2	1/2	-	0.173
$D_{15}(1675)$	1.676	5/2	1/2	-	0.159
$F_{15}(1680)$	1.684	5/2	1/2	+	0.139
$D_{33}(1700)$	1.762	3/2	3/2	-	0.599
$P_{13}(1720)$	1.717	3/2	1/2	+	0.383
$F_{35}(1905)$	1.881	5/2	3/2	+	0.327
$P_{31}(1910)$	1.882	1/2	3/2	+	0.239
$F_{37}(1950)$	1.945	7/2	3/2	+	0.300

Table 1: Properties of resonances that may contribute to the π production process. Here M_R is Breit-Wigner mass, J is spin, I is isospin, P is parity and Γ_0^{tot} is the vacuum total decay width at the pole of the resonances.



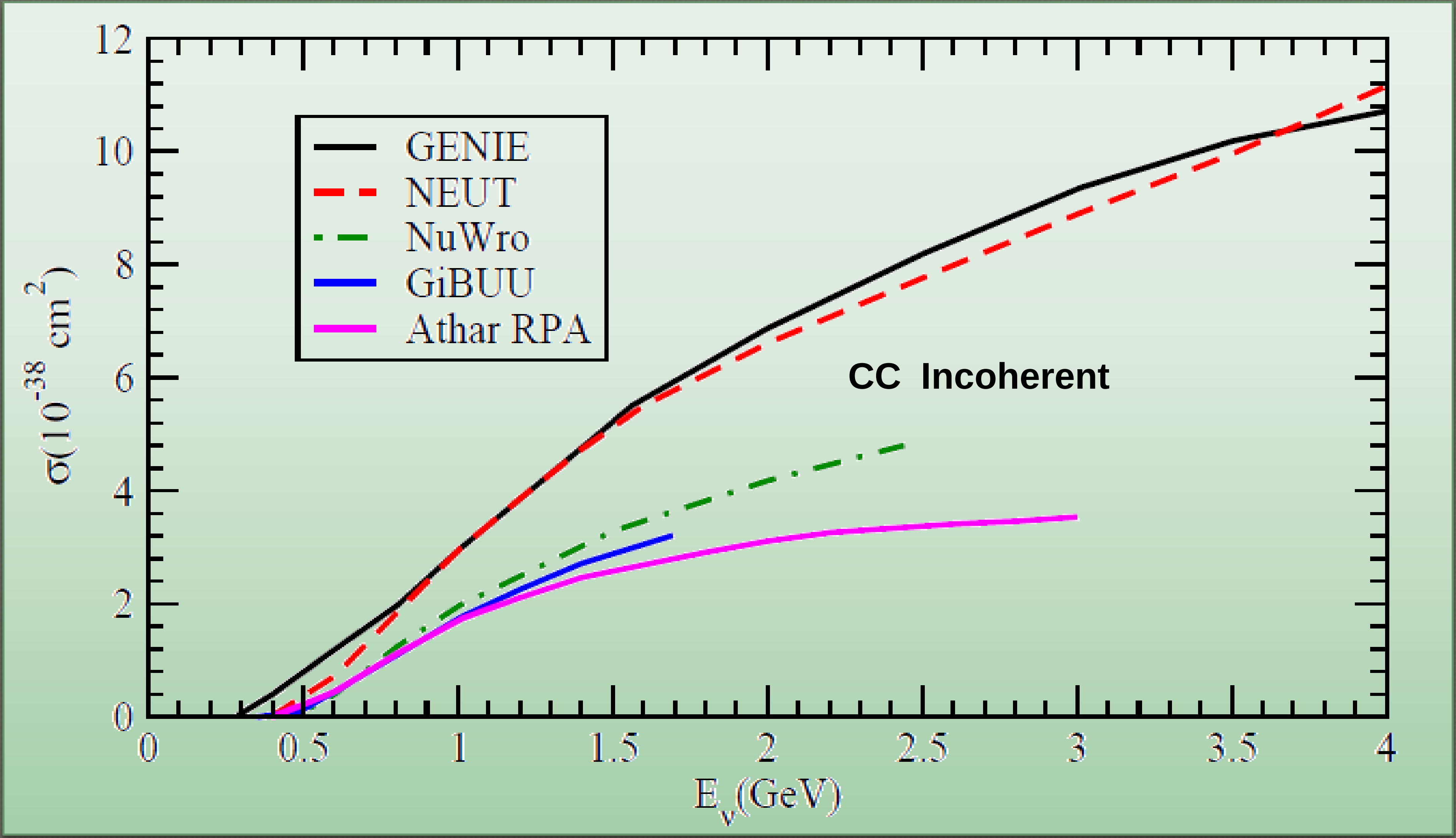
$\nu_\mu\, p \rightarrow \mu^- R^{++}$
(a)
$\nu_\mu\, n \rightarrow \mu^- R^{+}$
(b)
$\nu\, p \rightarrow \nu\, R^{+}$
(c)
$\nu\, n \rightarrow \nu\, R^{0}$
(d)
$P_{33}(1232)$
$P_{11}(1440)$
$D_{13}(1520)$
$S_{11}(1535)$
sum of all others
$\sigma\,[10^{-38}\ \mathrm{cm}^2]$
E_ν [GeV]
0.8
0.6
0.4
0.2
0
0.15
0.1
0.05
0.5
1
1.5
2

Differential cross section in the pion kinetic energy for ν_μ induced CC1π^+ production process in ^{12}C with ME + FSI effect



AIP Conf. Proc. 1189, 60 (2009)

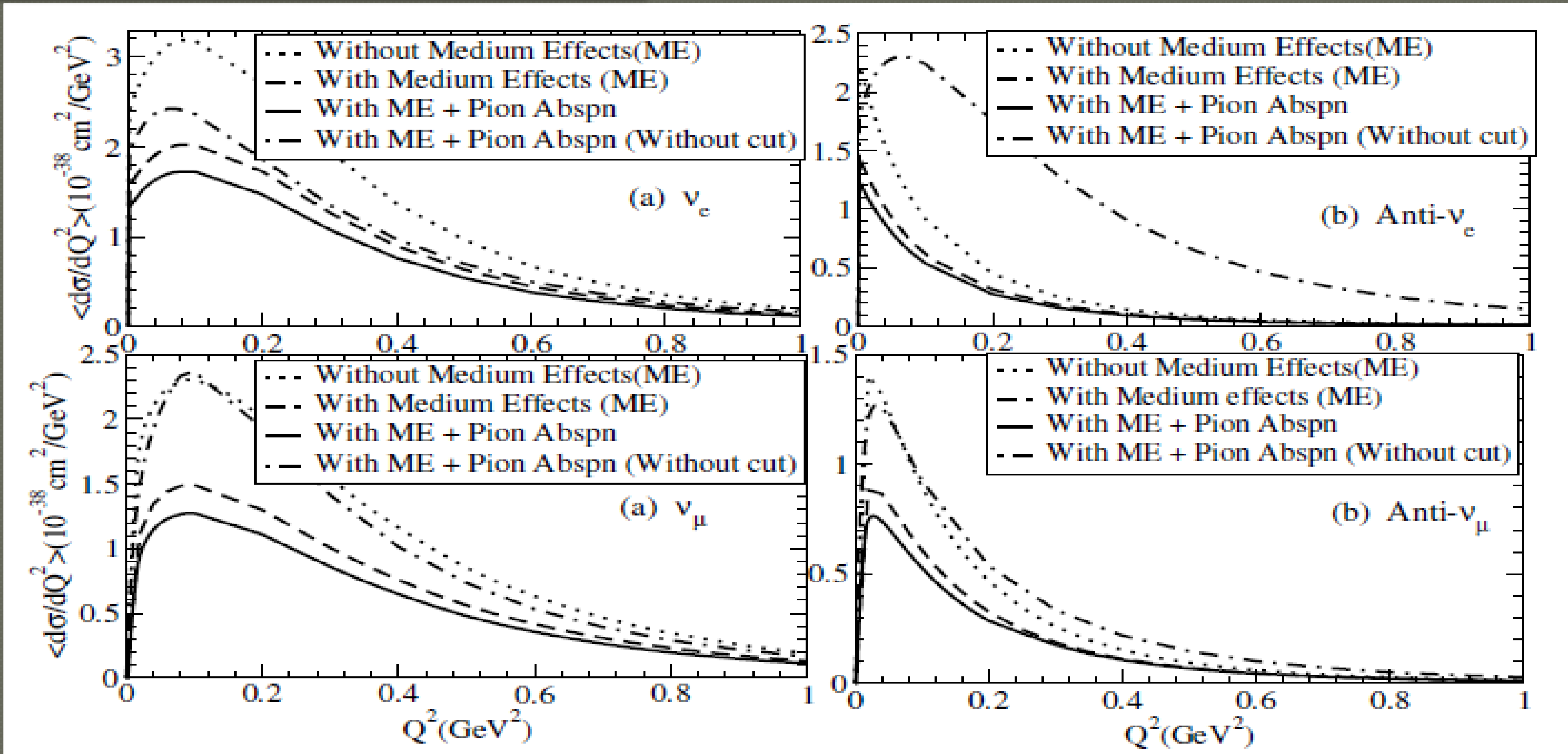
Total cross section for ν_μ induced CC1π production process in ^{12}C with ME + FSI effect



AIP Conf. Proc. 1189, 60 (2009)

Incoherent process

EPJA, 43 209 (2010)



% reduction in the distribution

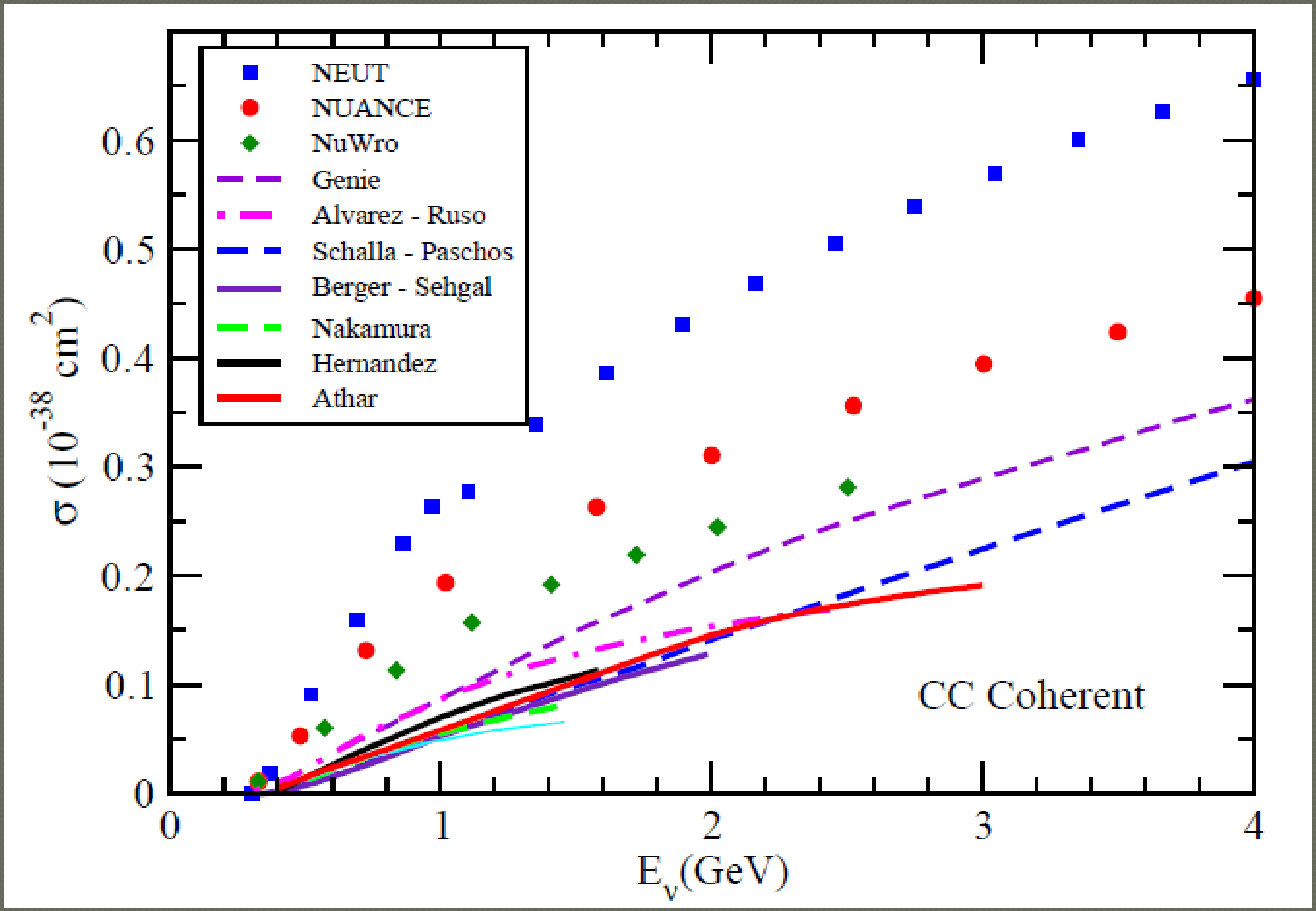
$Q^2\ (GeV^2)$	ME(without cut)	ME+FSI(Without cut)
Peak region(0.1)	35	14

Coherent Process

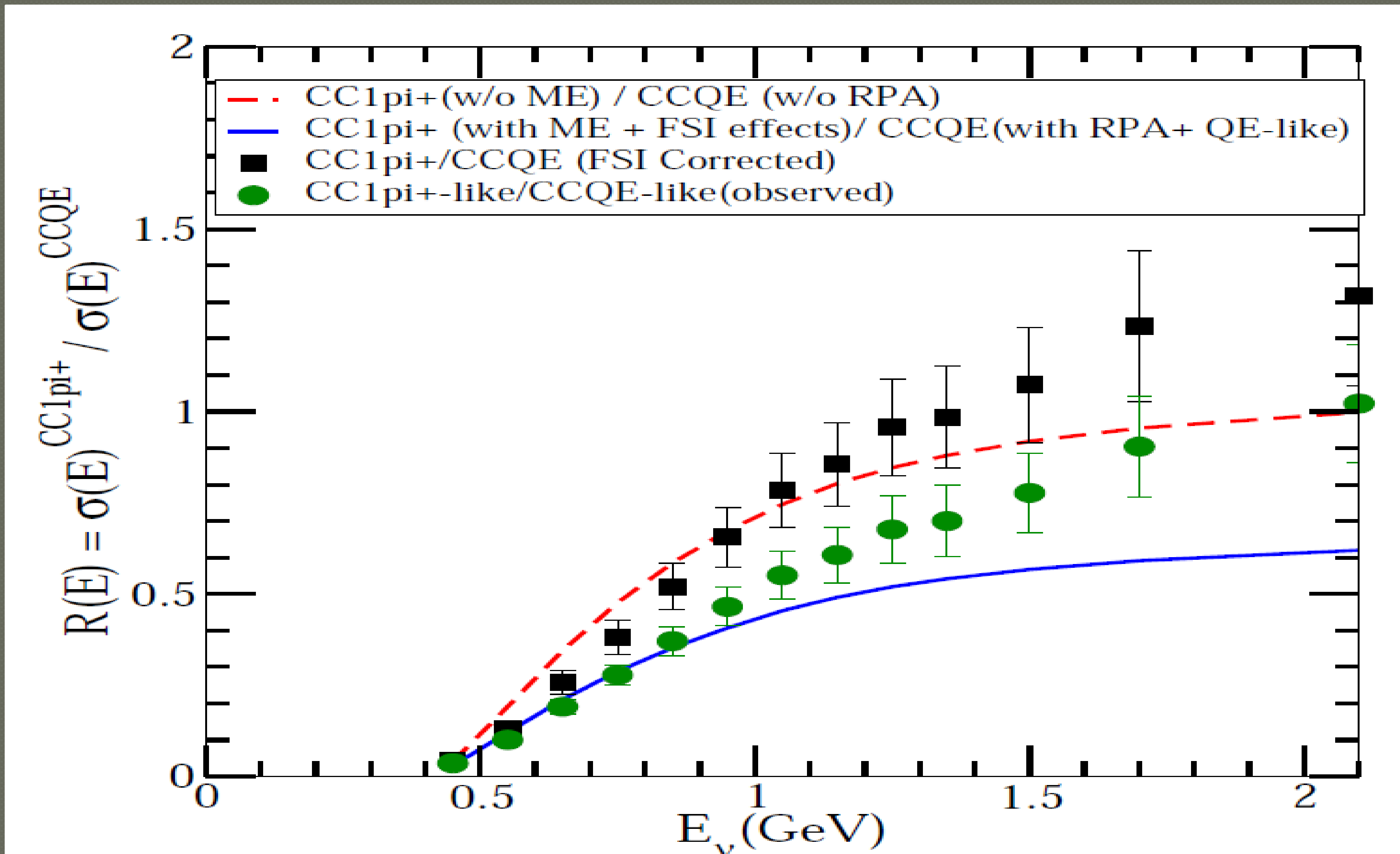
Nuclear effects in neutrino induced coherent pion production at K2K and MiniBooNE.

Phys. Rev. Lett. 96 (2006) 241801

Total cross section for ν_μ induced coherent CC1π^+ production process

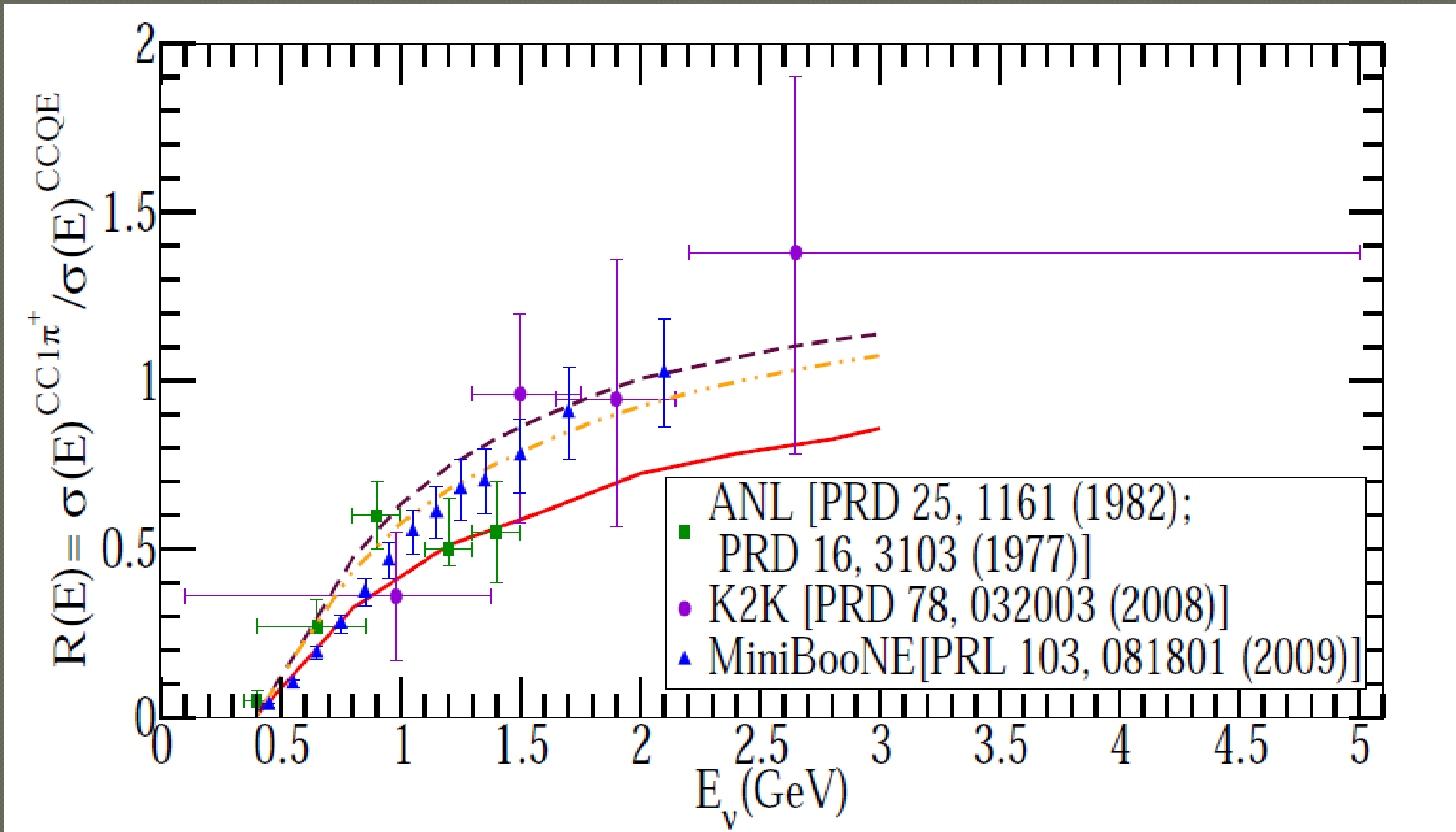


JPG 37, 015005 (2010)



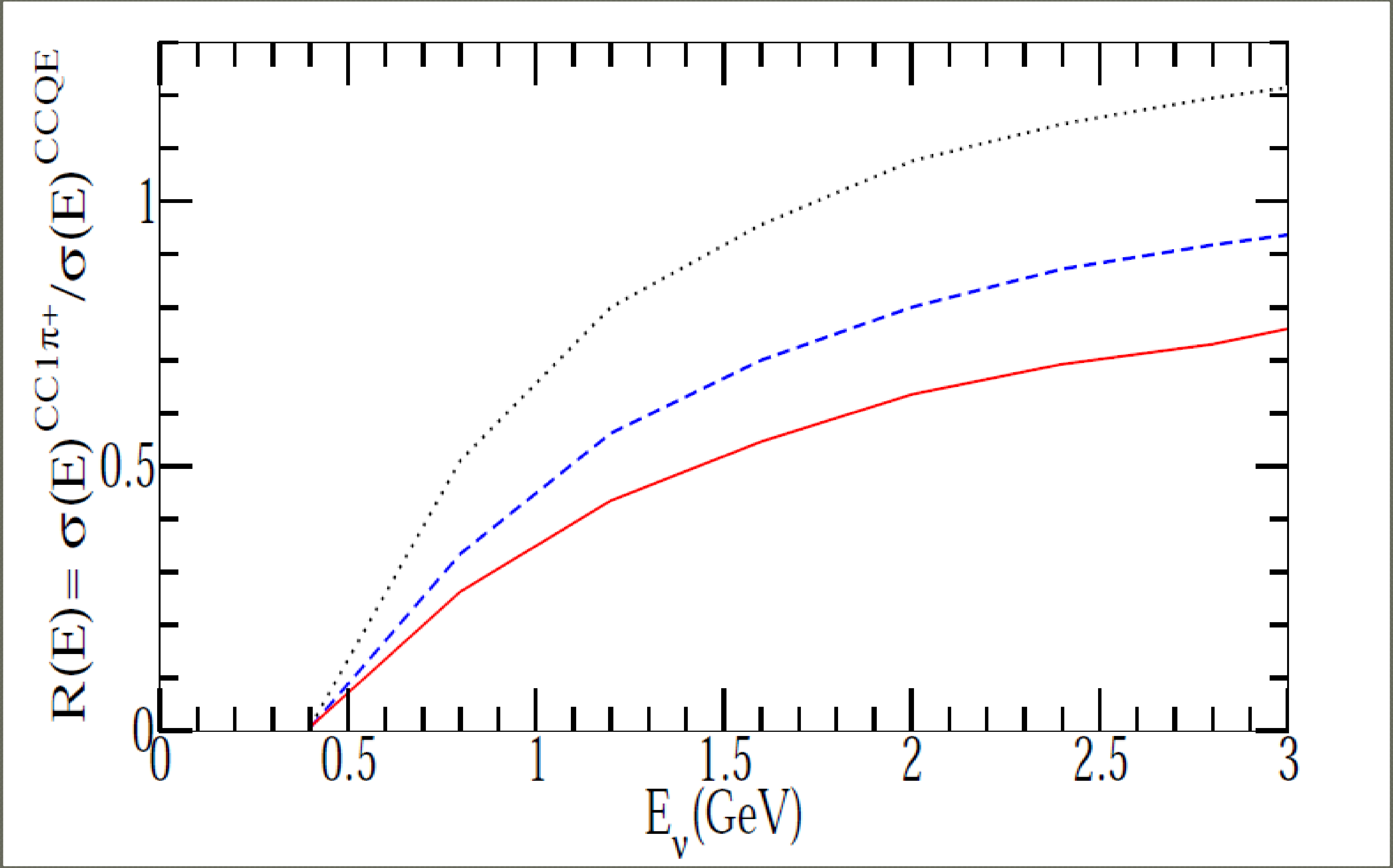
Ratio R(E) for Polystyrene(C_8H_8)

JPG 37, 015005 (2010)



Ratio R(E) in water (H_2O): T2K Experiment

JPG 37, 015005 (2010)



STRANGE PARTICLE PRODUCTION

- *Minerva experiment is planning to study strange particle production with high statistics.*

- *In performing the background studies in the analysis of neutrino oscillation experiments.*

- *In estimation of atmospheric neutrino ΔS backgrounds for nucleon-decay searches.*

LAGUNA plans to use detectors like GLACIER, MEMPHYS or LENA to test physics at the GUT scale

Extending the proton (and bound neutron) lifetime sensitivities up to 10^{35} years

K^+ life time ~ 12.8 ns and they decay into $K^+ \rightarrow \mu + \nu_\mu$ (63.43 %) or $K^+ \rightarrow \pi^+ + \pi^0$ (21.13 %)

Main background sources are muon neutrinos produced by cosmic rays interactions

These neutrinos interact with the detector producing muon in the energy range where search for proton decay is performed.

Different types of weak processes accompanying strange particle/particles

The first category comprises charged current $\Delta S = 0$ reactions:

$$
\begin{aligned}
\nu_l + n &\longrightarrow l^- + K^+ + \Lambda^0 \\
\nu_l + n &\longrightarrow l^- + \pi^0 + K^+ + \Lambda^0 \\
\nu_l + n &\longrightarrow l^- + \pi^+ + K^0 + \Lambda^0 \\
\nu_l + n &\longrightarrow l^- + K^- + K^+ + p \\
\nu_l + n &\longrightarrow l^- + K^+ + \pi^0 + p + \bar{K}^0
\end{aligned}
$$

Different types of weak processes accompanying strange particle/particles

Strange particle ΔS = 0 associated production can also proceed via Neutral Current reactions:

$$\nu_l + p \longrightarrow \nu_l + K^+ + \Lambda$$
$$\nu_l + n \longrightarrow \nu_l + K^0 + \Lambda$$
$$\nu_l + n \longrightarrow \nu_l + \pi^- + K^+ + \Lambda$$
$$\nu_l + p \longrightarrow \nu_l + K^+ + \Sigma^0$$
$$\nu_l + p \longrightarrow \nu_l + K^0 + \Sigma^+$$
$$\nu_l + n \longrightarrow \nu_l + K^+ + \Sigma^-$$
$$\nu_l + n \longrightarrow \nu_l + K^0 + \Sigma^0$$
$$\nu_l + n \longrightarrow \nu_l + K^- + \Sigma^+$$

Different types of weak processes accompanying strange particle/particles

Charged-current $\Delta S = 1$ reactions make up a second category. Produced final state contains single strange K-mesons. The reaction cross sections are Cabibbo suppressed relative to $\Delta S = 0$ reactions.

$$\nu_l + p \longrightarrow l^- + K^+ + p$$
$$\nu_l + n \longrightarrow l^- + K^0 + p$$
$$\nu_l + n \longrightarrow l^- + K^+ + n$$
$$\nu_l + n \longrightarrow l^- + \pi^+ + K^0 + n$$

(ΔS= 1 processes have no NC contributions as they involve a change in strangeness and therefore in charge.)

Different types of weak processes accompanying strange particle/particles

Δ S = Δ Q selection rule restricts Δ S = 1 single hyperon production to Anti-ν rather than ν reactions

$$\bar{\nu}_l + p \longrightarrow l^+ + \Lambda$$
$$\bar{\nu}_l + p \longrightarrow l^+ + \Sigma^0$$
$$\bar{\nu}_l + n \longrightarrow l^+ + \Sigma^-$$

Single Kaon Production

Single Kaon Production

PRD 82 (2010) 033001

$$\nu_l + p \longrightarrow l^- + K^+ + p$$
$$\nu_l + n \longrightarrow l^- + K^0 + p$$
$$\nu_l + n \longrightarrow l^- + K^+ + n$$

PRD 85 (2012) 013014

$$\overline{\nu}_l + p \longrightarrow l^+ + K^- + p$$
$$\overline{\nu}_l + p \longrightarrow l^+ + \overline{K}^0 + n$$
$$\overline{\nu}_l + n \longrightarrow l^+ + K^- + n$$

The basic reaction for the neutrino induced charged current kaon production is

$$\nu_l(k) + N(p) \rightarrow l^+(k' + K^-(p_k) + N(p')$$

for which the differential scattering cross section is given by

$$d^9\sigma = \frac{1}{4ME(2\pi)^5}\frac{d\vec{k}'}{(2E_l)}\frac{d\vec{p}'}{(2E_p')}\frac{d\vec{p}_k}{(2E_K)}\delta^4(k+p-k'-p'-p_k)\bar{\Sigma}\Sigma|\mathcal{M}|^2,$$

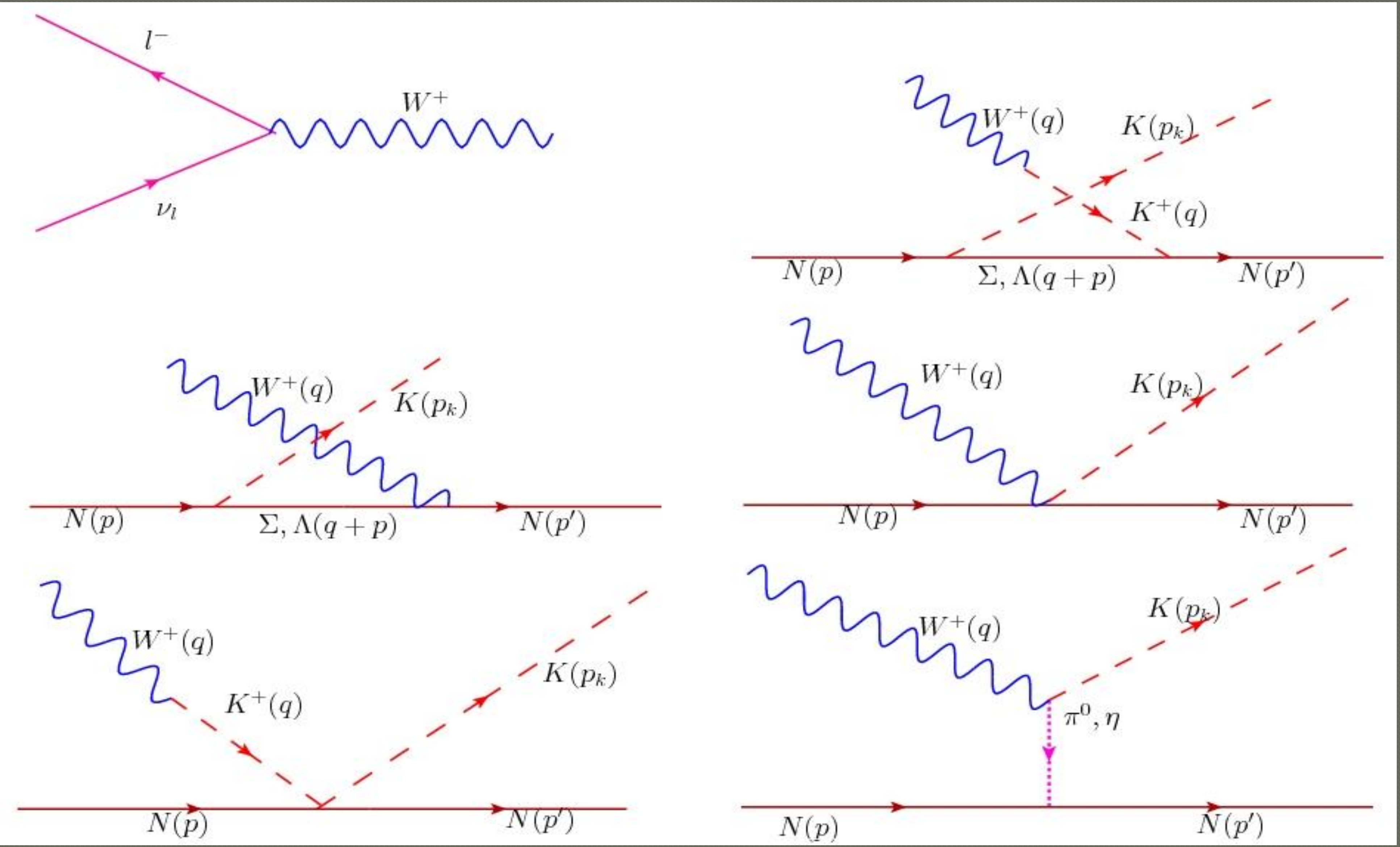
where M is the matrix element given by

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}\, j_\mu^{(L)}\, J^{\mu\,(H)} = \frac{g}{2\sqrt{2}} j_\mu^{(L)} \frac{1}{M_W^2} \frac{g}{2\sqrt{2}} J^{\mu\,(H)},$$

the leptonic current is given by,

$$\mathcal{L} = -\frac{g}{2\sqrt{2}}\left[W_\mu^+ \bar{\nu}_l \gamma^\mu (1-\gamma^5)\, l + W_\mu^- \bar{l}\, \gamma^\mu (1-\gamma^5)\nu_l\right]$$

Feynman diagrams for the neutrino induced process: u-channel Kaon in flight , u-channel, contact term, Kaon in flight, pion/eta in flight



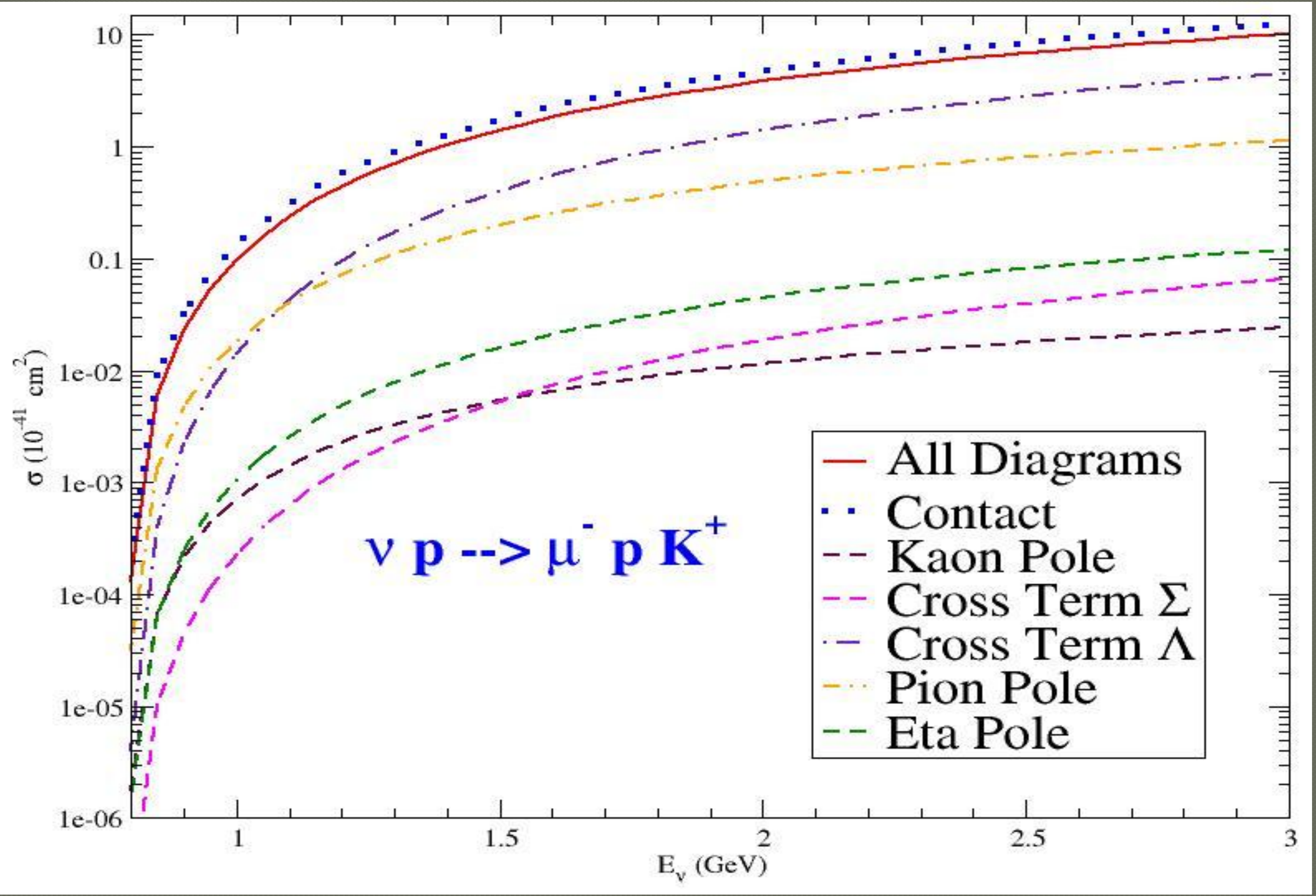
Contributions to the hadronic current for neutrino induced process

$$
\begin{aligned}
j^\mu\big|_{CT} &= -iA_{CT}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')(\gamma^\mu+\gamma^\mu\gamma^5 B_{CT})N(p),\\
j^\mu\big|_{Cr\Sigma} &= iA_{Cr\Sigma}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\left(\gamma^\mu+i\frac{\mu_p+2\mu_n}{2M}\sigma^{\mu\nu}q_\nu+(D-F)(\gamma^\mu-\frac{q^\mu}{q^2-M_k^2}\not{q})\gamma^5\right)\\
&\quad\times\frac{\not{p}-\not{p}_k+M_\Sigma}{(p-p_k)^2-M_\Sigma^2}\not{p}_k\gamma^5 N(p),\\
j^\mu\big|_{Cr\Lambda} &= iA_{Cr\Lambda}V_{us}\frac{\sqrt{2}}{4f_\pi}\bar{N}(p')\left(\gamma^\mu+i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu-\frac{D+3F}{3}(\gamma^\mu-\frac{q^\mu}{q^2-M_k^2}\not{q})\gamma^5\right)\\
&\quad\times\frac{\not{p}-\not{p}_k+M_\Lambda}{(p-p_k)^2-M_\Lambda^2}\not{p}_k\gamma^5 N(p),\\
j^\mu\big|_{KP} &= iA_{KP}V_{us}\frac{\sqrt{2}}{4f_\pi}\bar{N}(p')(\not{q}+\not{p}_k)N(p)\frac{1}{q^2-M_k^2}q^\mu,\\
j^\mu\big|_{\pi} &= iA_{\pi P}V_{us}(D+F)\frac{\sqrt{2}}{2f_\pi}\frac{M}{(q-p_k)^2-M_\pi^2}\bar{N}(p')\gamma^5.(q^\mu-2{p_k}^\mu)N(p),\\
j^\mu\big|_{\eta} &= iA_{\eta P}V_{us}(D-3F)\frac{\sqrt{2}}{2f_\pi}\frac{M}{(q-p_k)^2-M_\eta^2}\bar{N}(p')\gamma^5.(q^\mu-2{p_k}^\mu)N(p),
\end{aligned}
$$

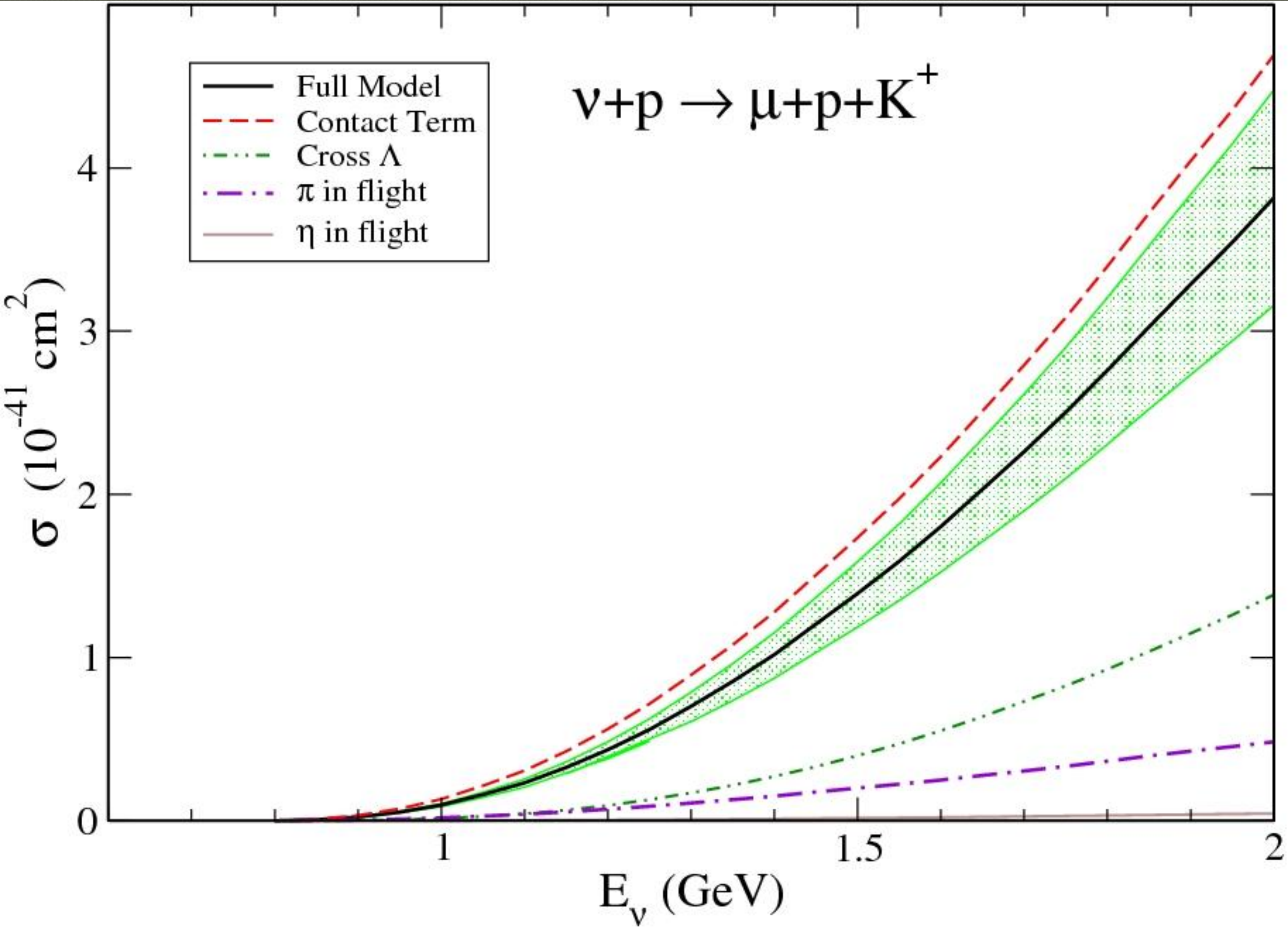
Contributions to the hadronic current for anti-neutrino induced process

$$
\begin{aligned}
J^\mu|_{CT} &= iA_{CT}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\left(\gamma^\mu + B_{CT}\,\gamma^\mu\gamma_5\right)N(p) \\
J^\mu|_{\Sigma} &= iA_\Sigma(D-F)V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{p}_k\gamma_5\frac{\not{p}+\not{q}+M_\Sigma}{(p+q)^2-M_\Sigma^2}\left(\gamma^\mu + i\frac{(\mu_p+2\mu_n)}{2M}\sigma^{\mu\nu}q_\nu\right. \\
&+ \left.(D-F)\left\{\gamma^\mu - \frac{q^\mu}{q^2-{M_k}^2}\not{q}\right\}\gamma^5\right)N(p) \\
J^\mu|_{\Lambda} &= iA_\Lambda V_{us}(D+3F)\frac{1}{2\sqrt{2}f_\pi}\bar{N}(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M_\Lambda}{(p+q)^2-M_\Lambda^2}\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu\right. \\
&- \left.\frac{(D+3F)}{3}\left\{\gamma^\mu - \frac{q^\mu}{q^2-{M_k}^2}\not{q}\right\}\gamma^5\right)N(p) \\
J^\mu|_{KP} &= iA_{KP}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{q}\,N(p)\frac{q^\mu}{q^2-M_k^2} \\
J^\mu|_{\pi} &= iA_\pi\frac{M\sqrt{2}}{2f_\pi}V_{us}(D+F)\frac{2{p_k}^\mu-q^\mu}{(q-p_k)^2-{m_\pi}^2}\bar{N}(p')\gamma_5 N(p) \\
J^\mu|_{\eta} &= iA_\eta\frac{M\sqrt{2}}{2f_\pi}V_{us}(D-3F)\frac{2{p_k}^\mu-q^\mu}{(q-p_k)^2-{m_\eta}^2}\bar{N}(p')\gamma_5 N(p) \\
J^\mu|_{\Sigma^*} &= -iA_{\Sigma^*}\frac{\mathcal{C}}{f_\pi}\frac{1}{\sqrt{6}}V_{us}\frac{p_k^\lambda}{P^2-M_{\Sigma^*}^2+i\Gamma_{\Sigma^*}M_{\Sigma^*}}\bar{N}(p')P_{RS_{\lambda\rho}}(\Gamma_V^{\rho\mu}+\Gamma_A^{\rho\mu})N(p)
\end{aligned}
$$

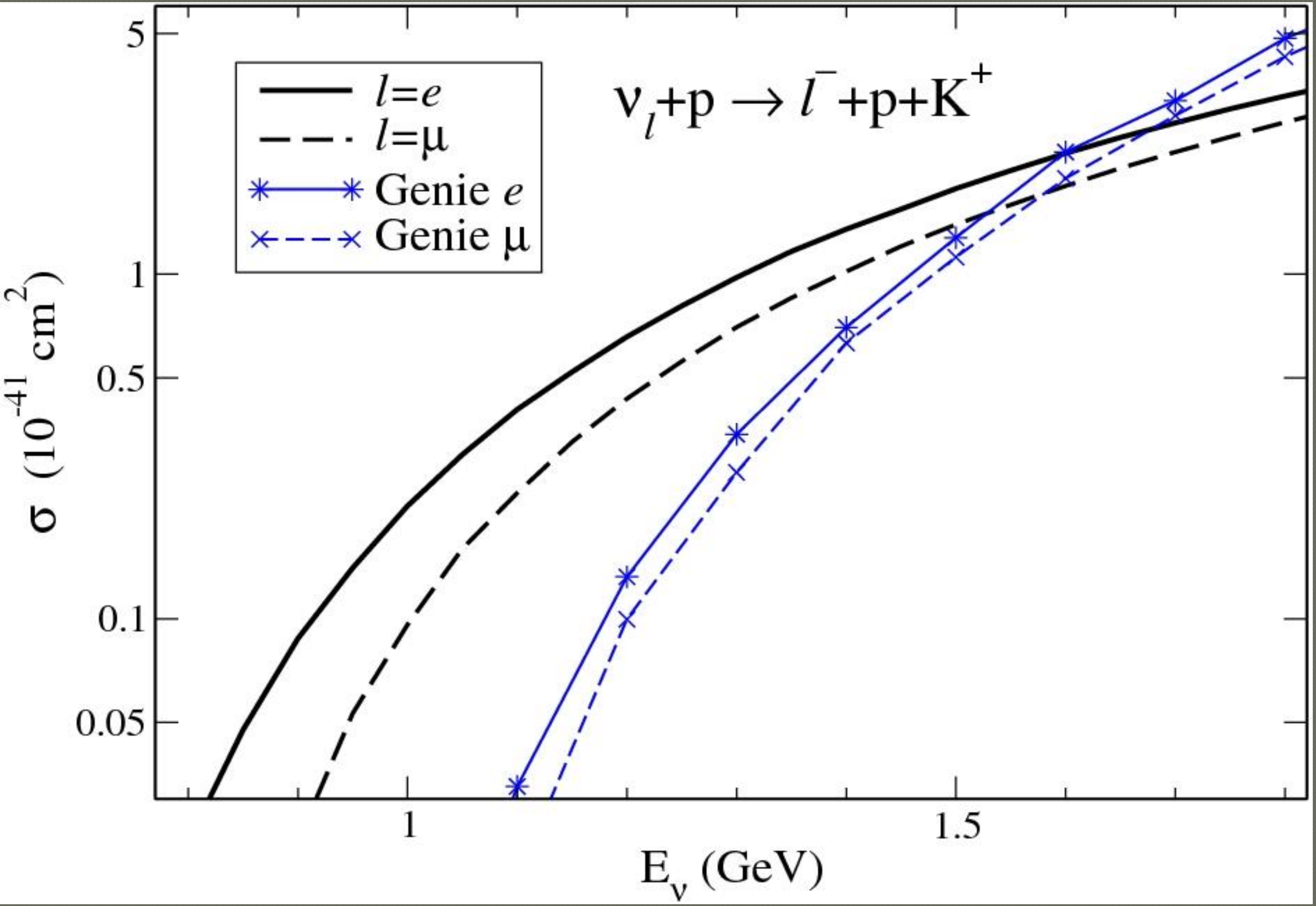
PRD 82,033001,2010



PHYSICAL REVIEW D 82, 033001 (2010)



PRD 82,033001,2010



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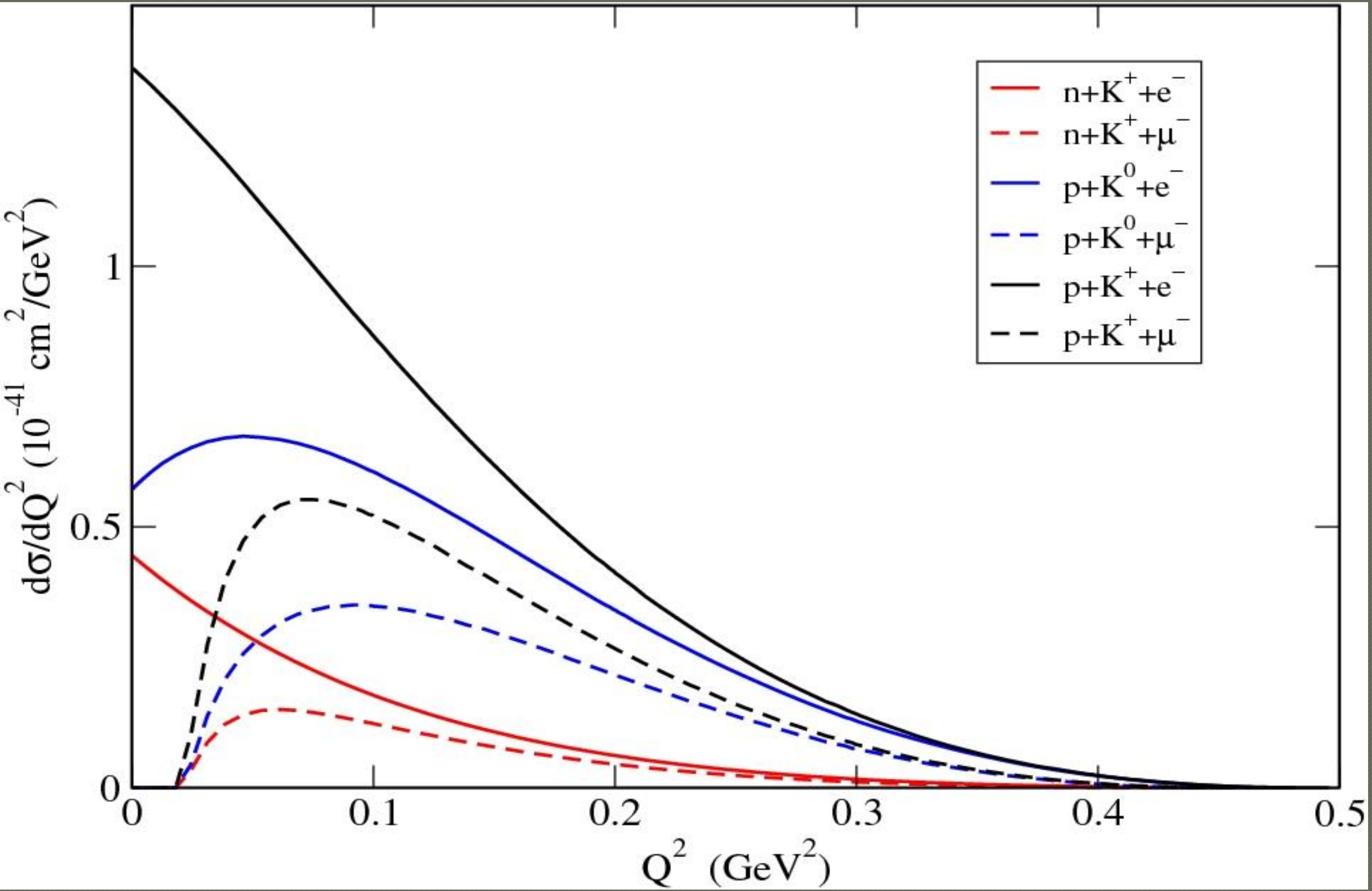
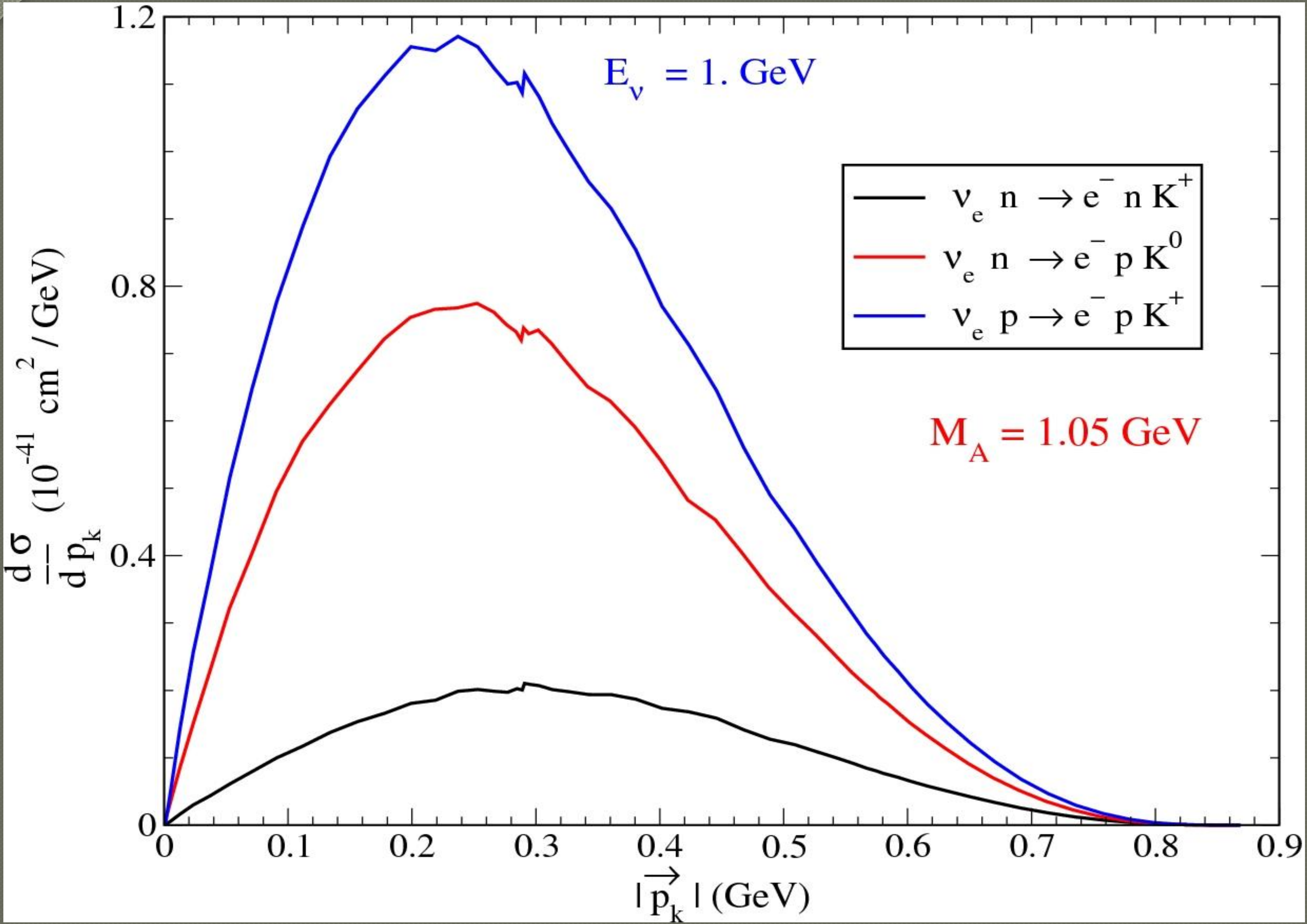
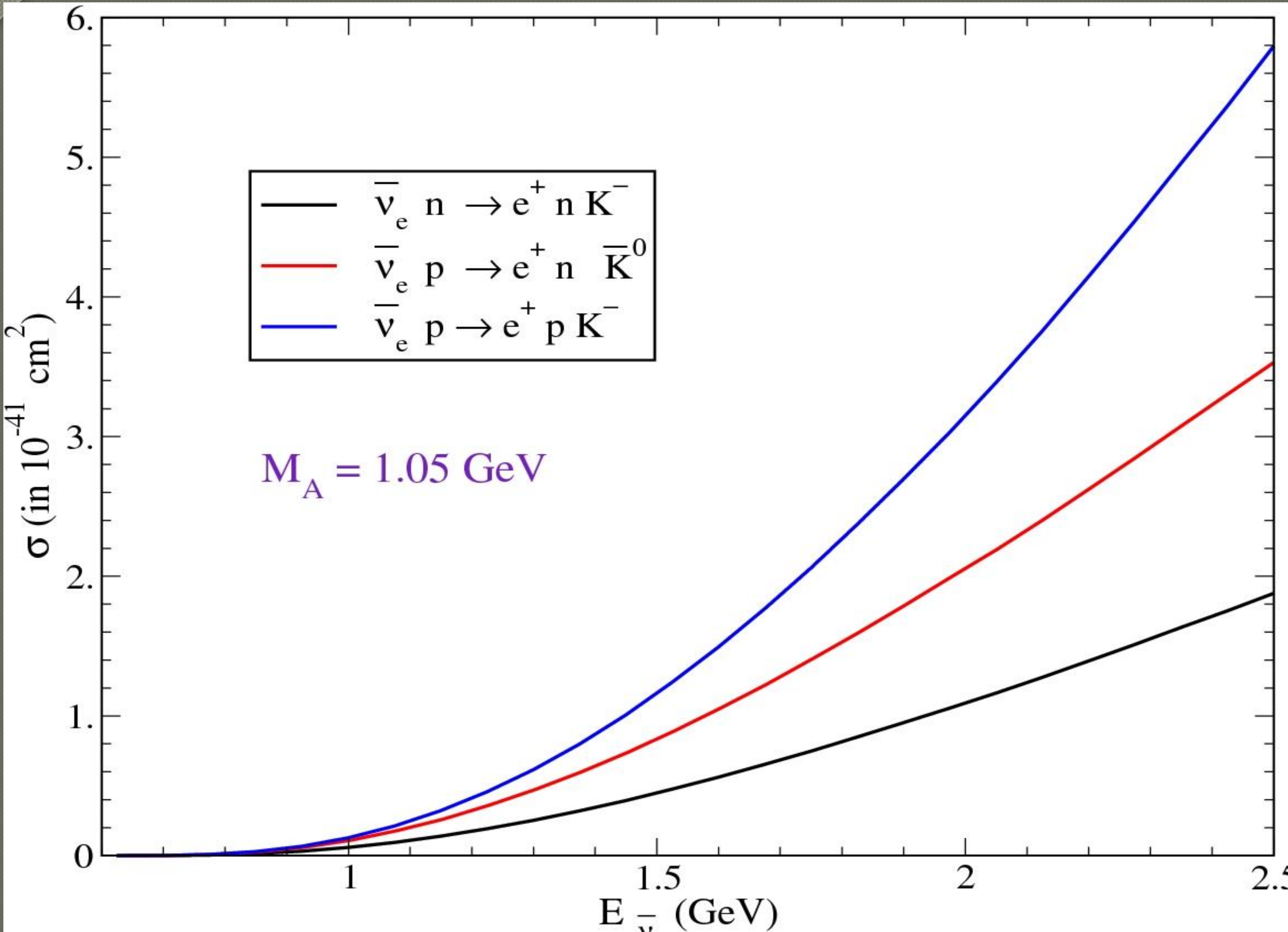




E_ν = 1. GeV
$\nu_e\ n \rightarrow e^-\ n\ K^+$
$\nu_e\ n \rightarrow e^-\ p\ K^0$
$\nu_e\ p \rightarrow e^-\ p\ K^+$
M_A = 1.05 GeV
$\frac{d\sigma}{dp_k}$ (10^{-41} cm^2 / GeV)
$|\vec{p_k}|$ (GeV)

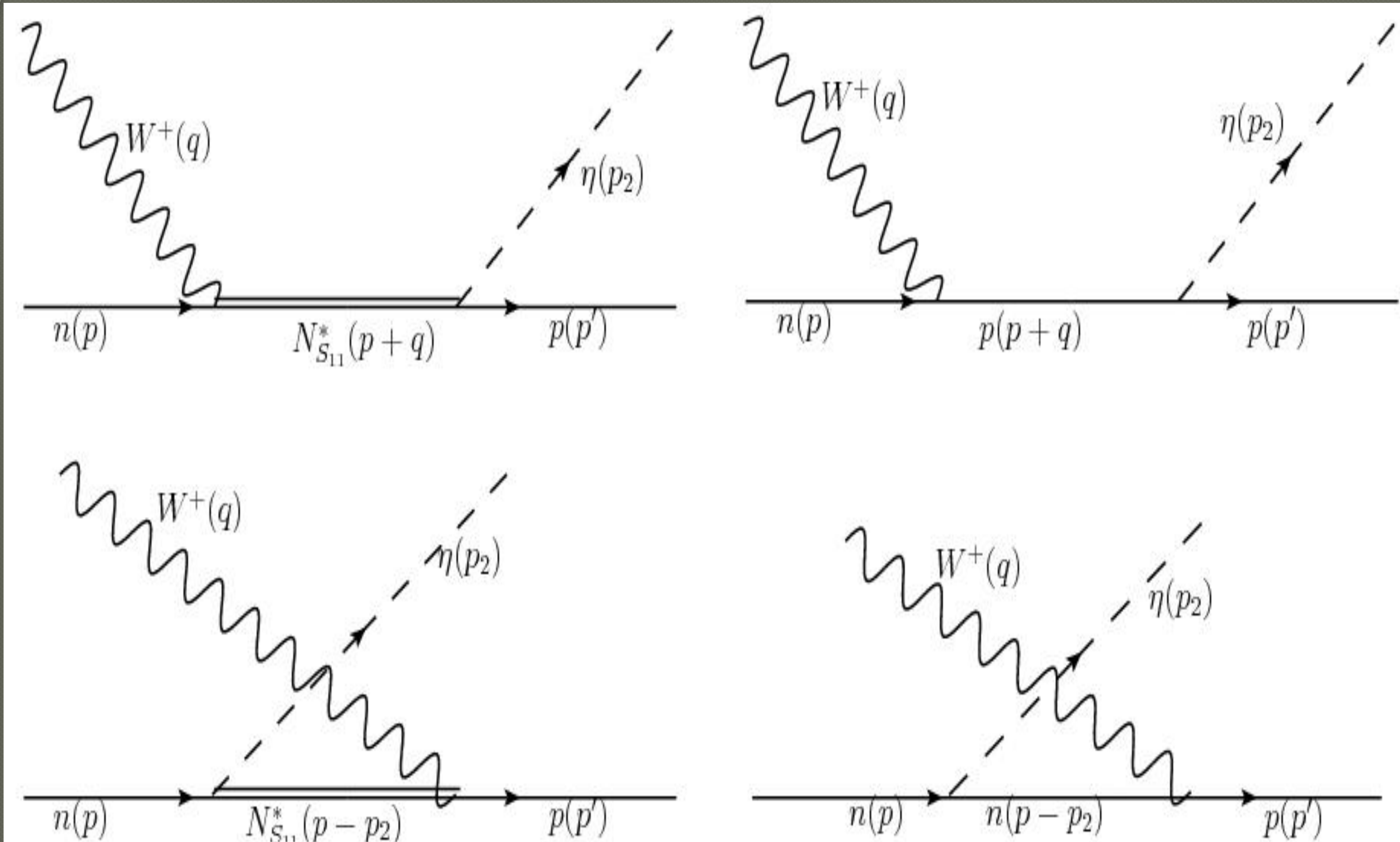
Flux averaged cross section for $\nu N \rightarrow lNK$ in 10^{-42} cm^2 at $M_A = 1$ GeV

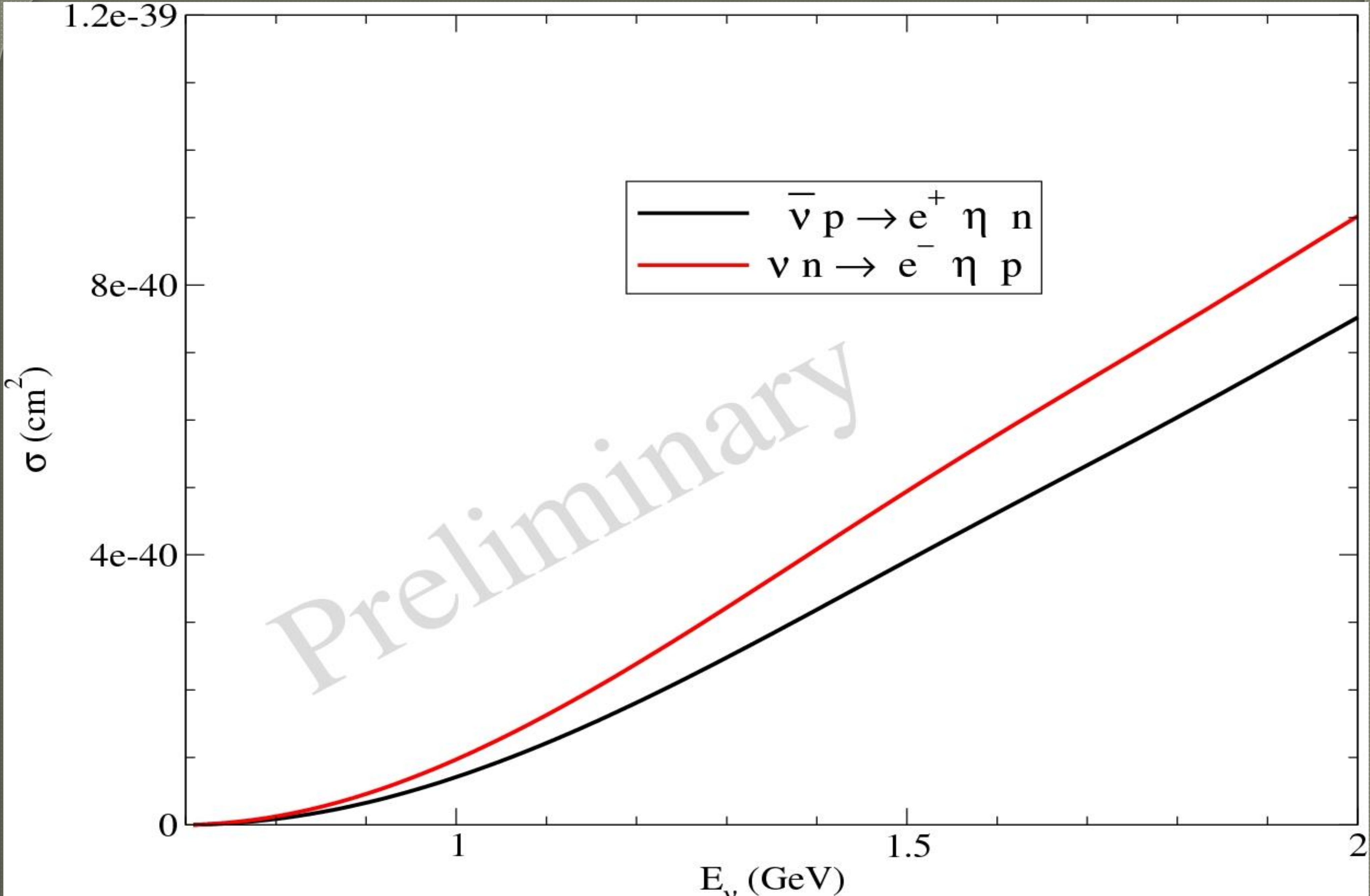
	ANL	MiniBooNE	T2K	Change in $< \sigma >$ with M_A= 1.1GeV
$\nu n \rightarrow \mu^- n K^+$	0.619	0.68	0.924	13-15 %
$\nu n \rightarrow \mu^- p K^0$	1.79	2.0	2.535	16-18 %
$\nu p \rightarrow \mu^- p K^+$	2.91	3.212	4.289	16-18 %
Total	5.319	5.895	7.748	



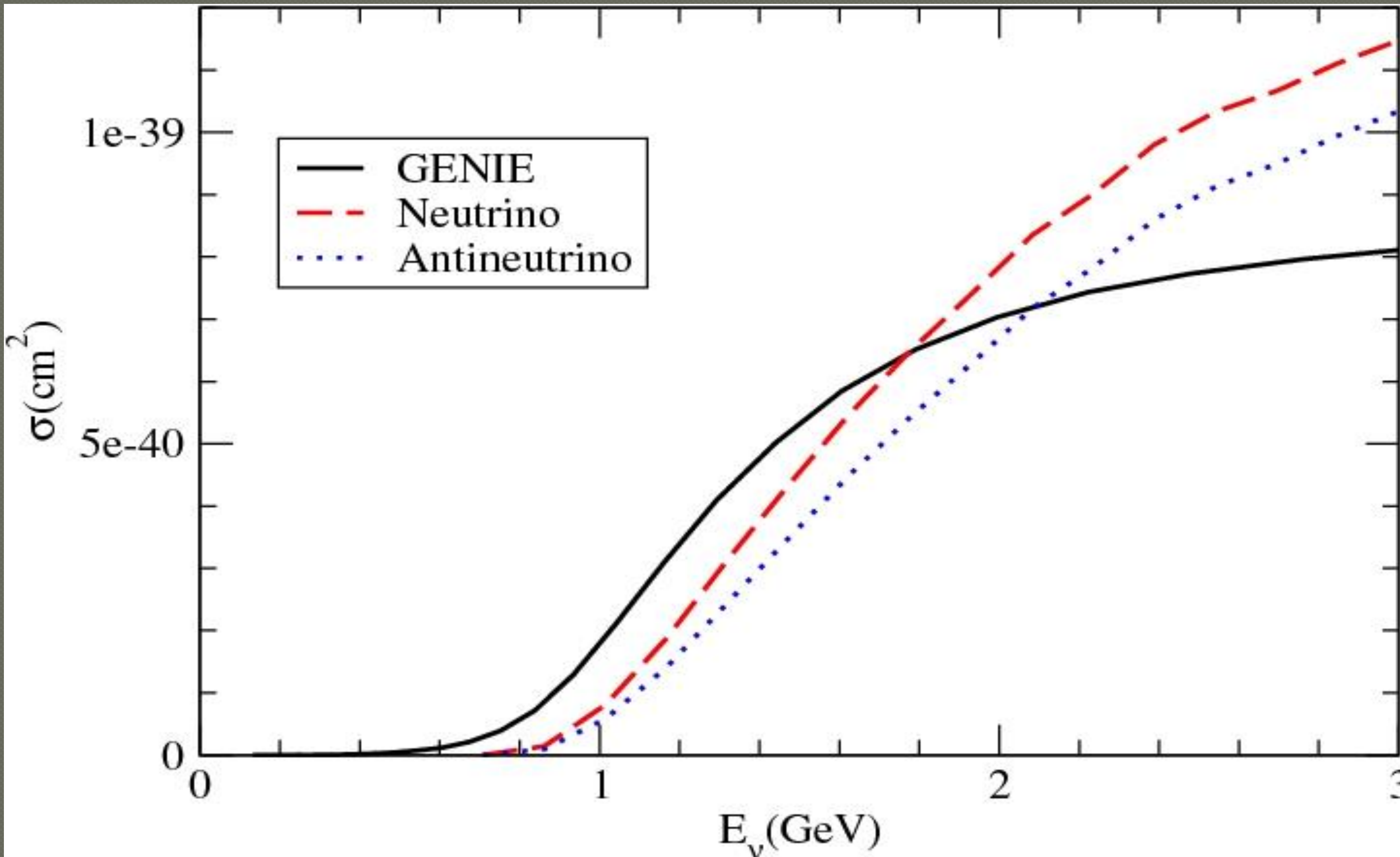
6.
5.
4.
3.
2.
1.
0
1
1.5
2
2.5
σ (in 10^{-41} cm^2)
$E_{\bar{\nu}}$ (GeV)
$\bar{\nu}_e\ n \rightarrow e^+\ n\ K^-$
$\bar{\nu}_e\ p \rightarrow e^+\ n\ \bar{K}^0$
$\bar{\nu}_e\ p \rightarrow e^+\ p\ K^-$
M_A = 1.05 GeV

Eta Production


$W^+(q)$
$\eta(p_2)$
$n(p)$
$N^*_{S_{11}}(p+q)$
$p(p')$
$W^+(q)$
$\eta(p_2)$
$n(p)$
$p(p+q)$
$p(p')$
$W^+(q)$
$\eta(p_2)$
$n(p)$
$N^*_{S_{11}}(p-p_2)$
$p(p')$
$W^+(q)$
$\eta(p_2)$
$n(p)$
$n(p-p_2)$
$p(p')$



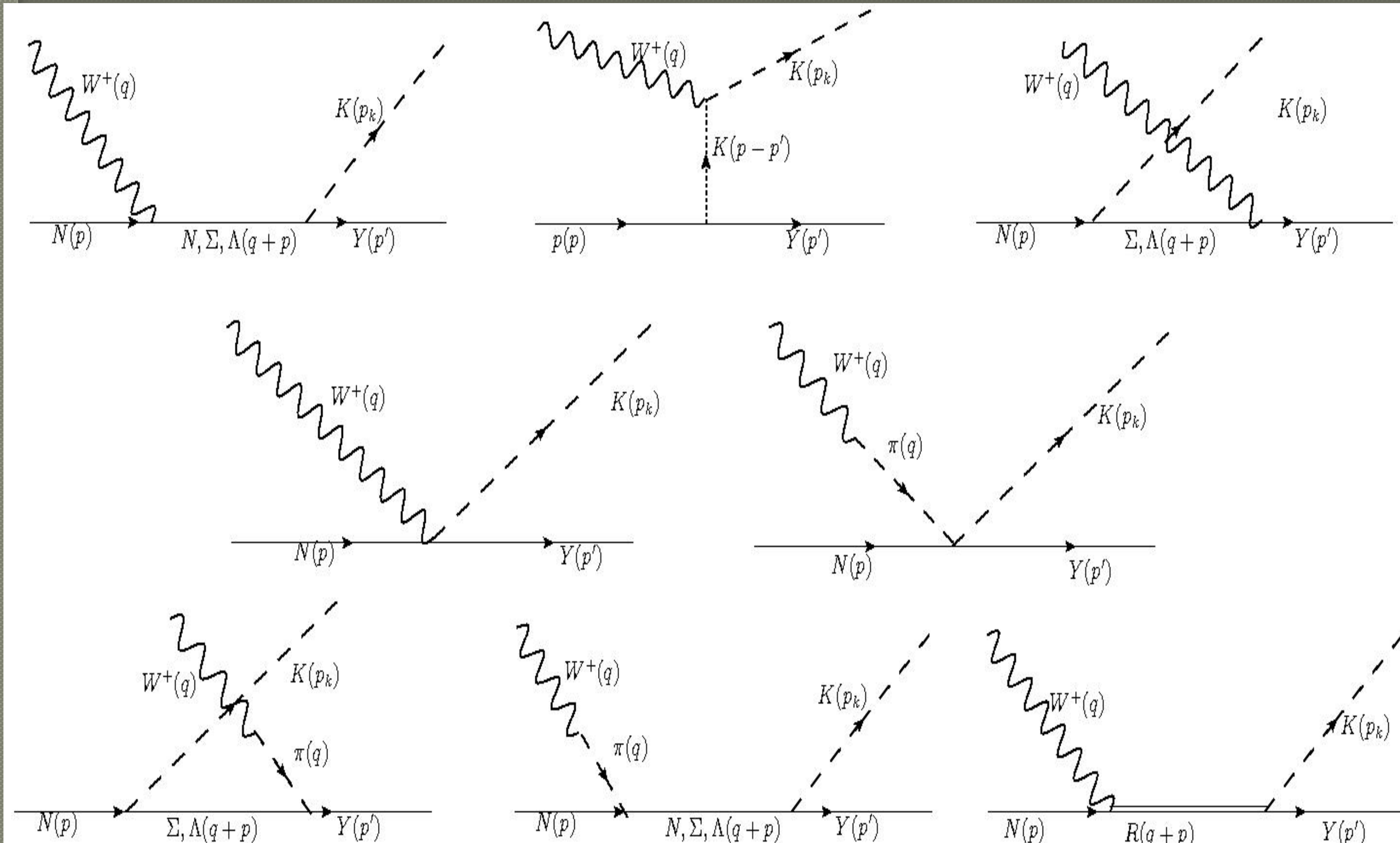
1.2e-39
8e-40
4e-40
0
σ (cm²)
1
1.5
2
E_ν (GeV)
$\bar{\nu}\, p \to e^+\, \eta\, n$
$\nu\, n \to e^-\, \eta\, p$
Preliminary



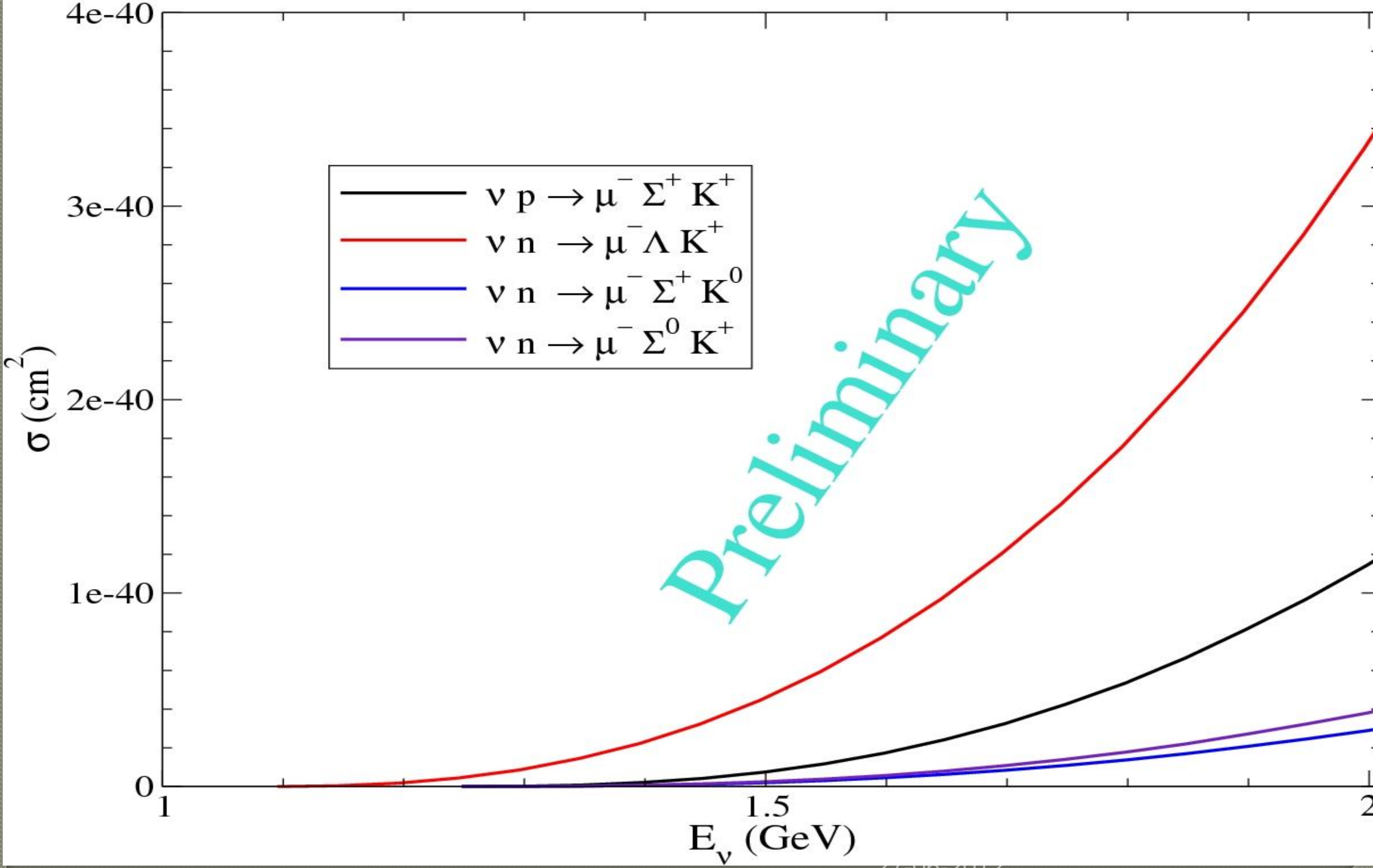
GENIE
Neutrino
Antineutrino
1e-39
5e-40
0
$\sigma(cm^2)$
0
1
2
3
E_ν(GeV)

Associated Production

Associated Production



BACKGROUND TERMS



DEEP INELASTIC SCATTERING (DIS)

Phenomenological and Theoretical studies of nuclear medium effects

Most of the study of nuclear medium effect in the case of ν(anti-ν)-A DIS has been done phenomenologically by the various groups like the works of

Hirai et al.(hep-ph/1102.3479)

Eskola et al.(JHEP 04 065 2009)

Kovarik et al.(PRL 106 122301 2011) and others

There are only a few calculations for the ν(anti-ν)-A DIS where the dynamical origin of nuclear medium effect has been considered.

Kulagin & Petti PRD 76 094023 2007

Our group ***PLB 668 133 (2008)***

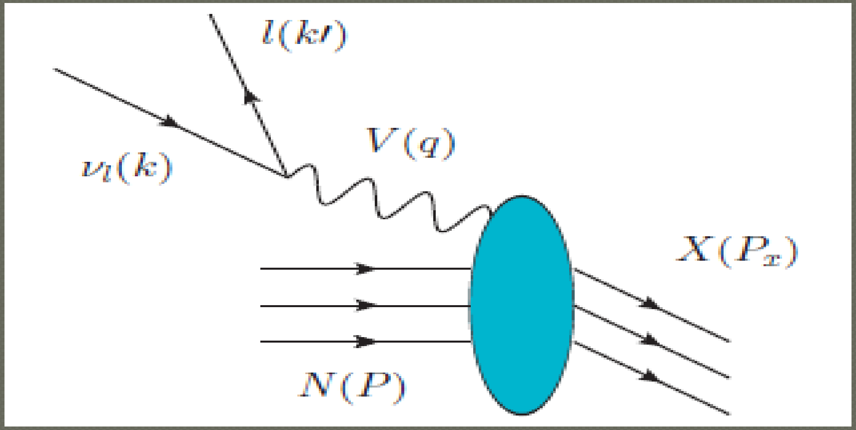
NPA 857 29 (2011)

PRC 84 054610 (2011)

PRC 85 055201 (2012)

These calculations have been performed to understand the contribution of various effects like Fermi motion, Pauli blocking, shadowing and anti-shadowing and pion and rho cloud contributions.

Deep Inelastic Scattering



The basic reaction for ν-N scattering is

$$\nu_l(k) + N(p) \to l^-(k') + X(p_x)$$

The differential scattering cross section of ν-N scattering is:

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

Hadronic tensor :

$$W_{\alpha\beta}^{N} = \left(\frac{q_\alpha q_\beta}{q^2} - g_{\alpha\beta}\right) W_1^{\nu(\bar{\nu})} + \frac{1}{M^2}\left(p_\alpha - \frac{p.q}{q^2} q_\alpha\right)\left(p_\beta - \frac{p.q}{q^2} q_\beta\right) W_2^{\nu(\bar{\nu})} - \frac{i}{2M^2}\epsilon_{\alpha\beta\rho\sigma} p^\rho q^\sigma W_3^{\nu(\bar{\nu})}$$
$$+ \frac{1}{M^2} q_\alpha q_\beta W_4^{\nu(\bar{\nu})} + \frac{1}{M^2}(p_\alpha q_\beta + q_\alpha p_\beta) W_5^{\nu(\bar{\nu})}$$

Leptonic tensor :

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

Differential scattering cross section:

Fermi coupling constant

$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\ dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left\{(y^2x + \frac{m_l^2 y}{2E_\nu M_N})F_1^{W^\pm}\right.$$
$$+ \left[(1-\frac{m_l^2}{4E_\nu^2}) - (1+\frac{M_N x}{2E_\nu})y\right] F_2^{W^\pm}$$
$$\pm \left[xy(1-\frac{y}{2}) - \frac{m_l^2 y}{4E_\nu M_N}\right] F_3^{W^\pm}$$
$$\left. + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_4^{W^\pm} - \frac{m_l^2}{E_\nu M_N}F_5^{W^\pm}\right\}$$

$$\frac{Q^2}{2M_N\nu}$$

where

$$F_1^{\nu(\bar\nu)}(x,Q^2) = MW_1^{\nu(\bar\nu)}(\nu,Q^2)$$
$$F_2^{\nu(\bar\nu)}(x,Q^2) = \nu W_2^{\nu(\bar\nu)}(\nu,Q^2)$$
$$F_3^{\nu(\bar\nu)}(x,Q^2) = \nu W_3^{\nu(\bar\nu)}(\nu,Q^2)$$

$$\frac{\nu}{E_\nu}$$

$$\frac{p.q}{M_N}$$

The structure functions $F_2(x)$ and $F_3(x)$ are given as

$$F_2^{\nu p} = 2x[d(x)+s(x)+\bar{u}(x)+\bar{c}(x)+b(x)+\bar{t}(x)]$$

$$F_2^{\nu n} = 2x[u(x)+s(x)+\bar{d}(x)+\bar{c}(x)+b(x)+\bar{t}(x)]$$

$$F_2^{\bar{\nu} p} = 2x[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)+t(x)+\bar{b}(x)]$$

$$F_2^{\bar{\nu} n} = 2x[d(x)+c(x)+\bar{u}(x)+\bar{s}(x)+t(x)+\bar{b}(x)]$$

$$F_3^{\nu p} = 2[d(x)+s(x)-\bar{u}(x)-\bar{c}(x)+b(x)-\bar{t}(x)]$$

$$F_3^{\nu n} = 2[u(x)+s(x)-\bar{d}(x)-\bar{c}(x)+b(x)-\bar{t}(x)]$$

$$F_3^{\bar{\nu} p} = 2[u(x)+c(x)-\bar{d}(x)-\bar{s}(x)+t(x)-\bar{b}(x)]$$

$$F_3^{\bar{\nu} n} = 2[d(x)+c(x)-\bar{u}(x)-\bar{s}(x)+t(x)-\bar{b}(x)]$$

Using Callan Gross relation

$$F_1(x) = F_2(x)/2x$$

✓We use a theoretical spectral function to describe the momentum distribution of nucleons in nuclei.

✓The spectral functions has been calculated using Lehmann's representation for the relativistic nucleon propagator.

✓Nuclear many body theory is used to calculate it for an interacting Fermi sea in nuclear matter.

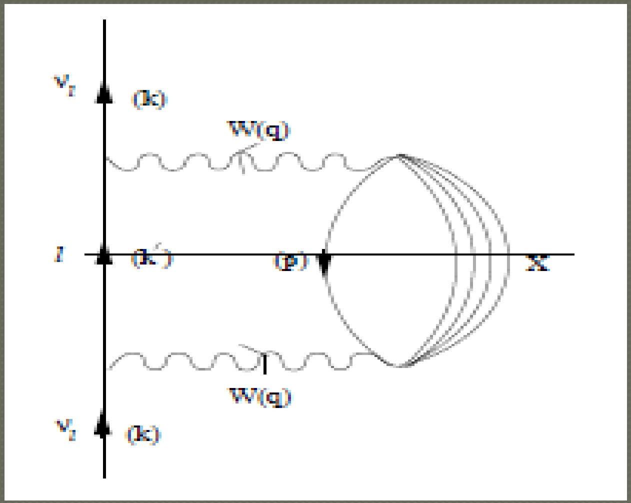
✓A local density approximation is then applied to translate these results to finite nuclei.

P. Fernandez de Cordoba and E. Oset, **Phys. Rev. C 46 1697 (1992).**
E. Marco, E. Oset and P. Fernandez de Cordoba, **Nucl. Phys. A 611 (1996) 484**

In the present formalism the neutrino – nucleus cross sections are obtained in terms of neutrino self energy Σ(k) in the nuclear medium:

The probability per unit time for the neutrino to collide with nucleons when travelling through nuclear matter is:

$$\Gamma(k) = -\frac{2m_\nu}{E_\nu(|\vec{k}|)}\,\mathrm{Im}\,\Sigma(k)$$



$$-i\sum(k) = \int \frac{d^4q}{(2\pi)^4}\bar{u}_\nu(k)\left(-\frac{ie}{2\sqrt{2}sin\theta_W}\gamma^\mu(1-\gamma_5)\right)\left(\frac{i(\not{k}'+m_l)}{k'^2-m_l^2+i\epsilon}\right)\left(-\frac{ie}{2\sqrt{2}sin\theta_W}\gamma^\nu(1-\gamma_5)\right)$$

$$u_\nu(k)\left(-i\frac{\left(g_{\mu\rho}-\frac{q_\mu q_\rho}{M_W^2}\right)}{q^2-M_W^2}\right)(-i)\Pi^{\rho\sigma}(q)\,i\frac{\left(g_{\sigma\nu}-\frac{q_\sigma q_\nu}{M_W^2}\right)}{q^2-M_W^2}$$

The total cross section for neutrino scattering from an element of volume d^3r and surface dS in the nucleus is given by

$$d\sigma = \Gamma dt ds = \Gamma \frac{dt}{dl} dl ds = \frac{\Gamma}{v} d^3 r = \Gamma \frac{E_\nu(\vec{K})}{|\vec{K}|} d^3 r = -\frac{2m_\nu}{|\vec{K}|} Im\Sigma d^3 r$$

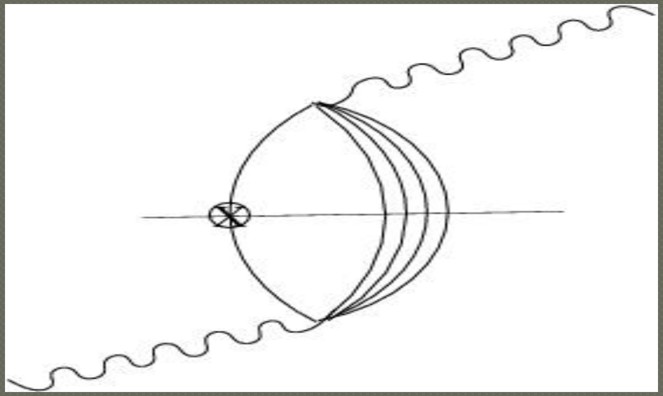
$$\Gamma(k) = -\frac{2m_\nu}{E_\nu(|\vec{k}|)} \operatorname{Im} \Sigma(k)$$

$\Pi_{\alpha\beta}$ is the W self energy in the nuclear medium

$$-i\Pi^{\alpha\beta}(q) = (-)\int \frac{d^4p}{(2\pi)^4} iG(p) \sum_X \sum_{s_p,s_i} \prod_{i=1}^{n} \int \frac{d^4p'_i}{(2\pi)^4} \prod_l iG_l(p'_l) \prod_j iD_j(p'_j) \left(\frac{-G_F m_W^2}{\sqrt{2}}\right)$$

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

The imaginary part of the neutrino self energy is evaluated by means of Cutkosky rules by cutting the Feynman diagram of W self energy along the horizontal line which puts the particles corresponding to the cut propagators on the mass shell by replacing the fermion and meson propagators by their imaginary part as



$$\begin{aligned} \Sigma(k) &\rightarrow 2iIm\Sigma(k) \\ D(p_j') &\rightarrow 2i\theta(p_{0j})\ ImD(p_j') \\ G(p_l') &\rightarrow 2i\theta(p_{0l}')\ ImG(p_l') \\ \frac{1}{k'^2 - m_l^2 + i\epsilon} &\rightarrow 2\pi\delta(k'^2 - m_l^2). \end{aligned}$$

The $F_2{}^A$ structure function in nucleus for electromagnetic interactions is:

$$F_2^A(x_A, Q^2) = 4 \int d^3r \int \frac{d^3p}{(2\pi)^3} \int_{-\infty}^{\mu} d\omega \, S_h(\omega, \mathbf{p}, \rho(\mathbf{r})) \frac{\left(1 - \frac{\gamma p_z}{M}\right)}{\gamma^2} \left(\gamma'^2 + \frac{6x_N^2(\mathbf{p}^2 - p_z^2)}{Q^2}\right) F_2^N(x_N, Q^2)$$

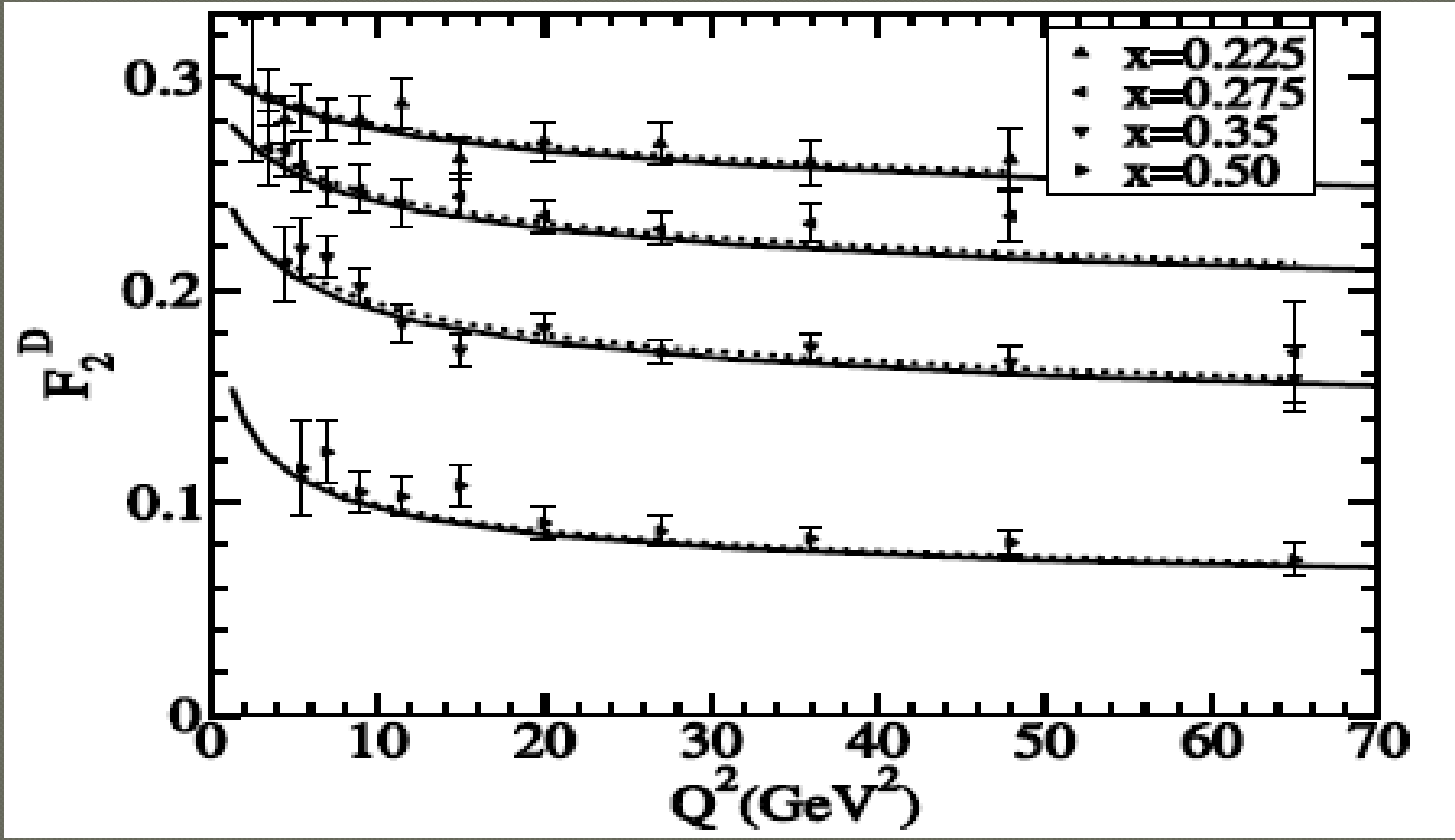
where

$$\gamma' = 1 + \frac{4x_N^2 p^2}{Q^2} \qquad x_N = \frac{Q^2}{2p.q}$$

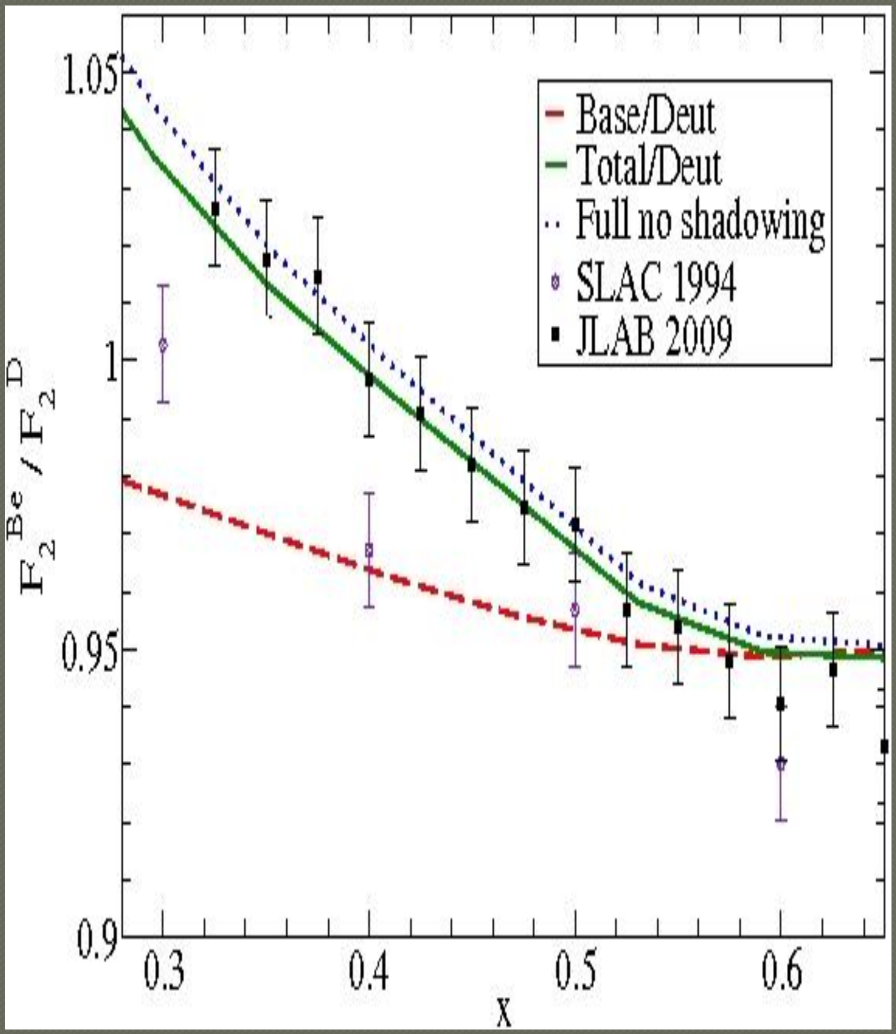
The deuteron structure function has been calculated using the same formalism as we have used for $F_2{}^A$ for a general nucleus , but performing the convolution with the deuteron wave function squared instead of spectral function which is written as:

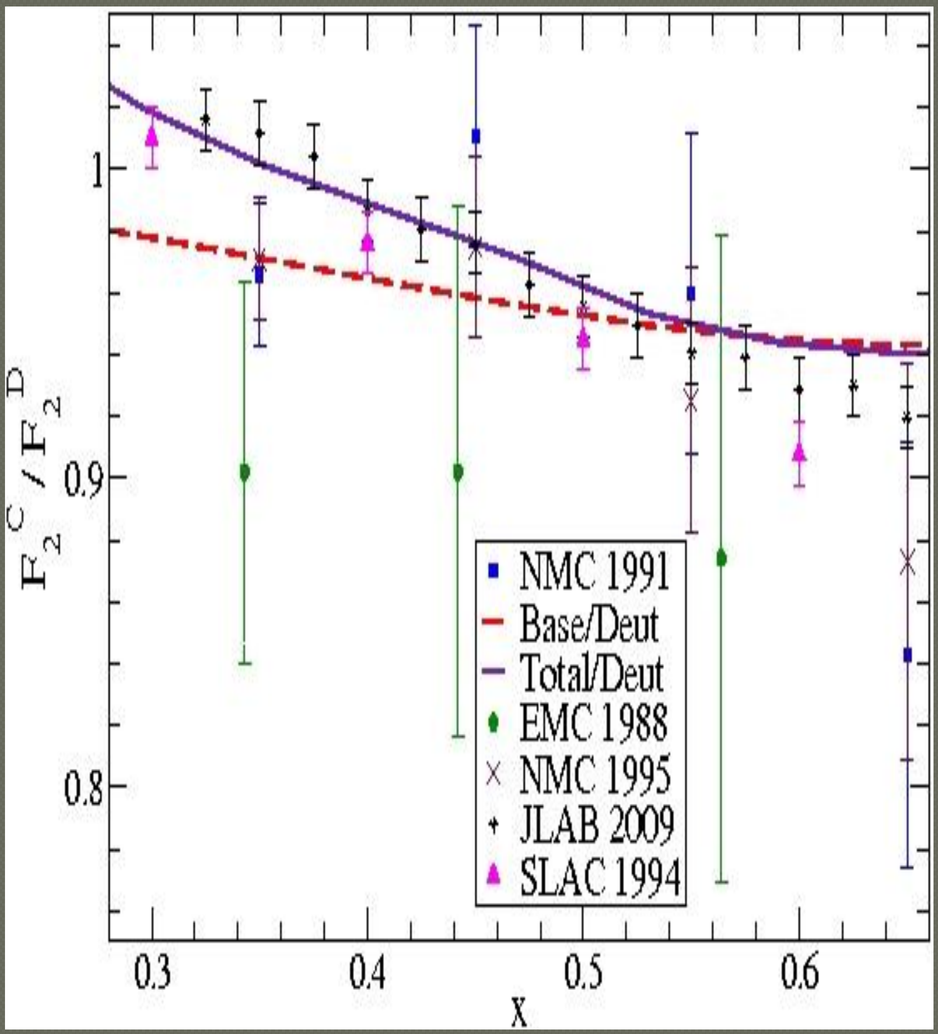
$$F_2^D(x, Q^2) \quad = \quad \int \frac{1}{\gamma^2} \quad \frac{d\mathbf{p}}{(2\pi)^3} \, |\Psi_D(\mathbf{p})|^2 \left(1 - \frac{\gamma p_z}{M}\right) \left(\gamma'^2 + \frac{6x_N{}^2 \mathbf{p}_\perp^2}{Q^2}\right) F_2^N$$

Electromagnetic structure function in deuteron



Ratio F_2^{Be}/F_2^D vs x and F_2^C/F_2^D vs x





M S A, I. Ruiz Simo and M. J. Vicente Vacas Nucl. Phys. A 857, 29 (2011)

The expression of F_2^A and F_3^A structure function due to nuclear medium effects like Fermi motion and binding energy in the present model are obtained as:

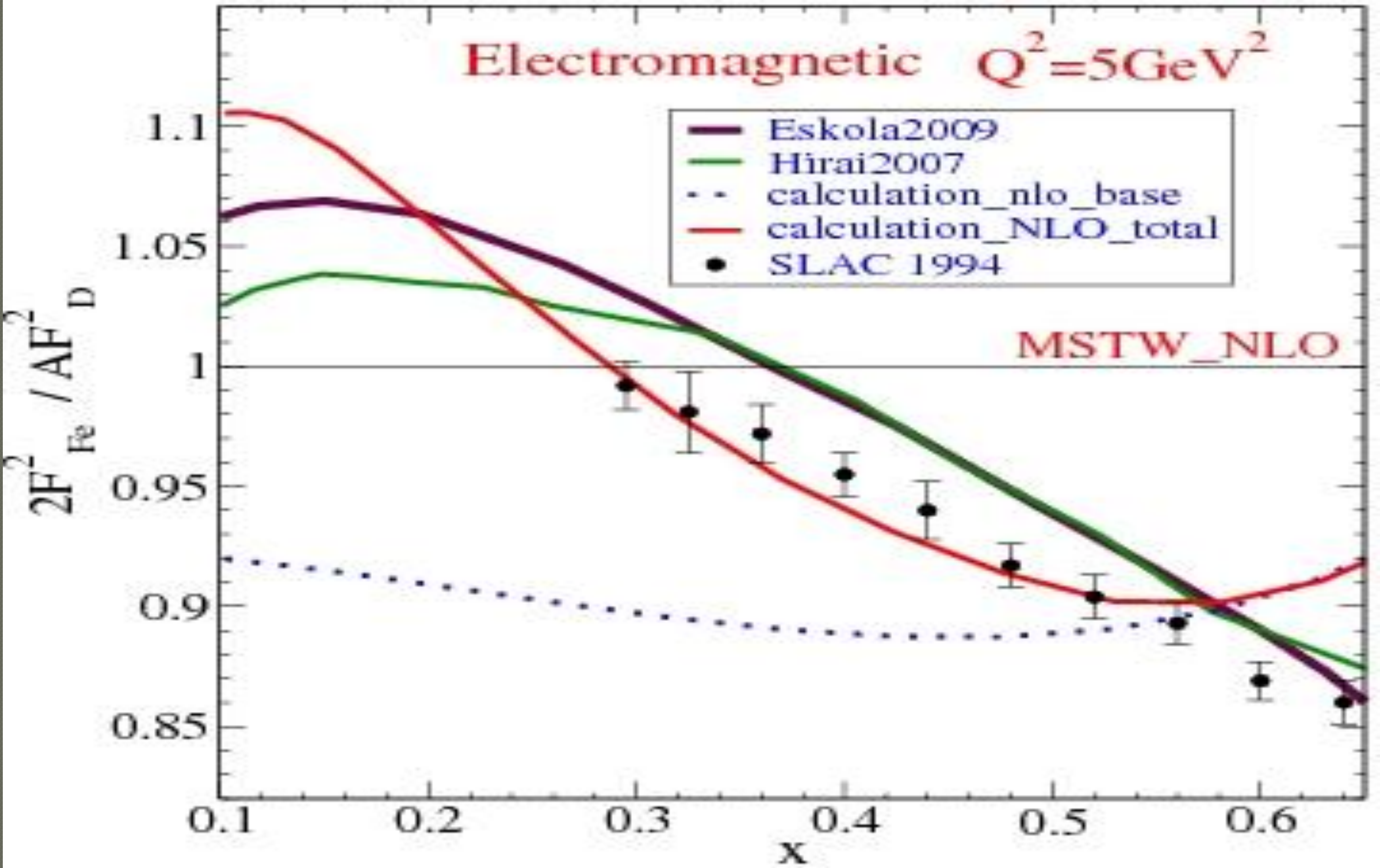
$$F_2^A(x_A, Q^2) = 4 \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(\mathbf{p})} \int_{-\infty}^{\mu} dp^0 \; S_h(p^0, \mathbf{p}, \rho(\mathbf{r})) \frac{x}{x_N} \left(1 + \frac{2x_N p_x^2}{M\nu_N}\right) F_2^N(x_N, Q^2)$$

$$F_3^A(x_A, Q^2) = 4 \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(\mathbf{p})} \int_{-\infty}^{\mu} dp^0 S_h(p^0, \mathbf{p}, \rho(\mathbf{r})) \frac{p^0\gamma - p_z}{(p^0 - p_z\gamma)\gamma} F_3^N(x_N, Q^2)$$

Defining γ as

$$\gamma = \frac{q_z}{q^0} = \left(1 + \frac{4M^2x^2}{Q^2}\right)^{1/2},$$

F_2^{Fe} / F_2^D vs x in Iron



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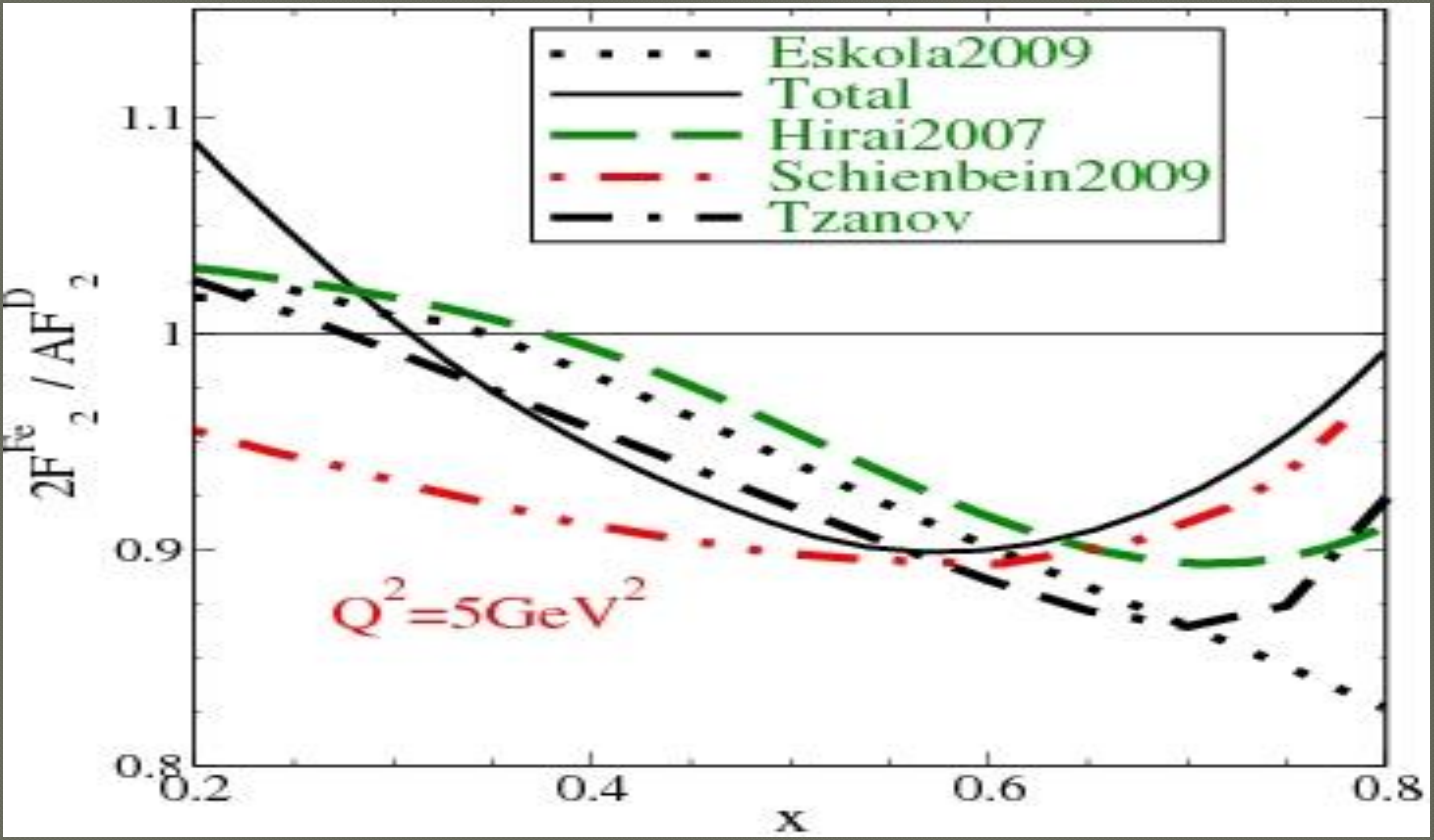
F^2_{Fe} / F^2_D vs x in Iron



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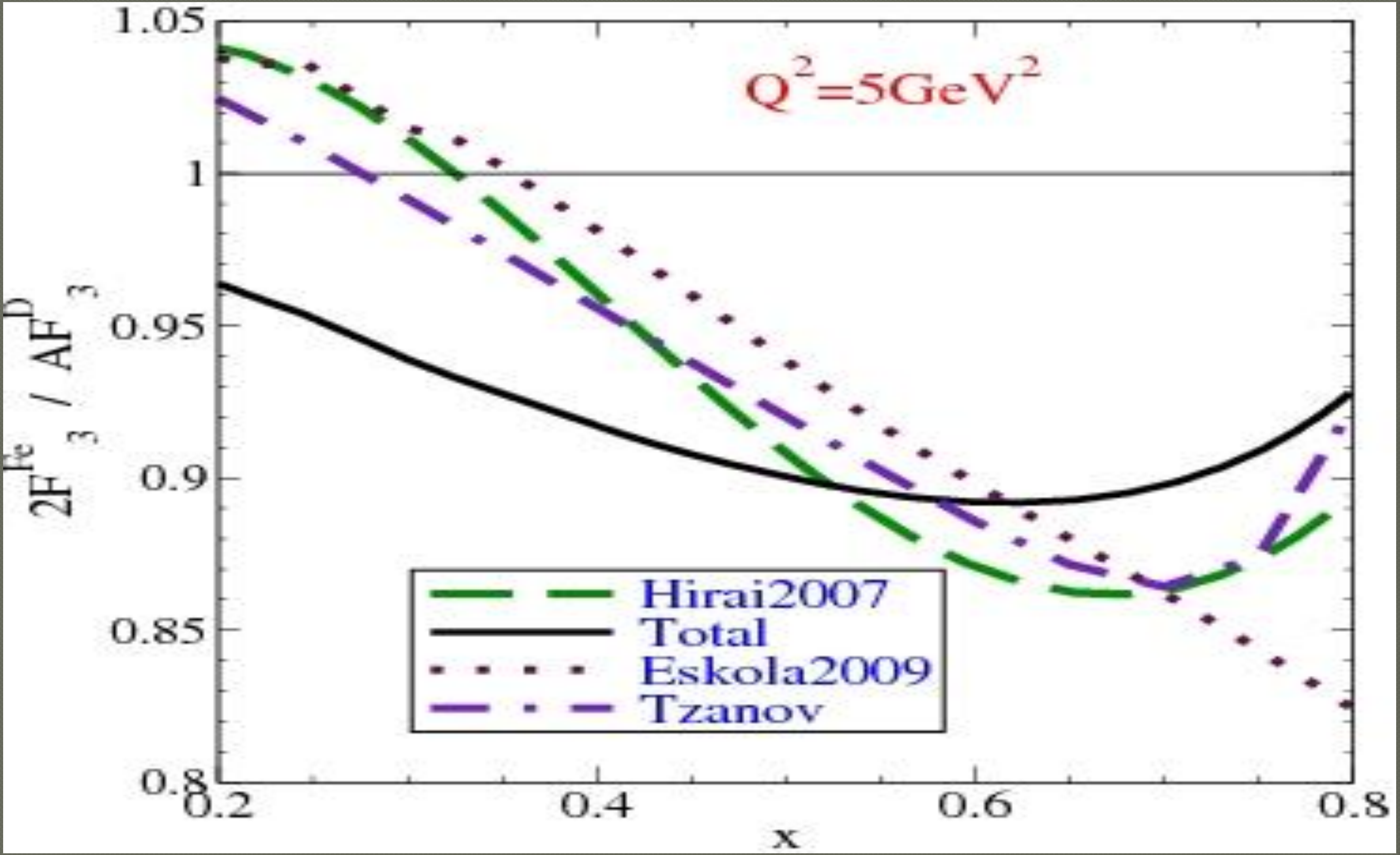
F_3^{Fe} / F_3^{D} vs x in Iron



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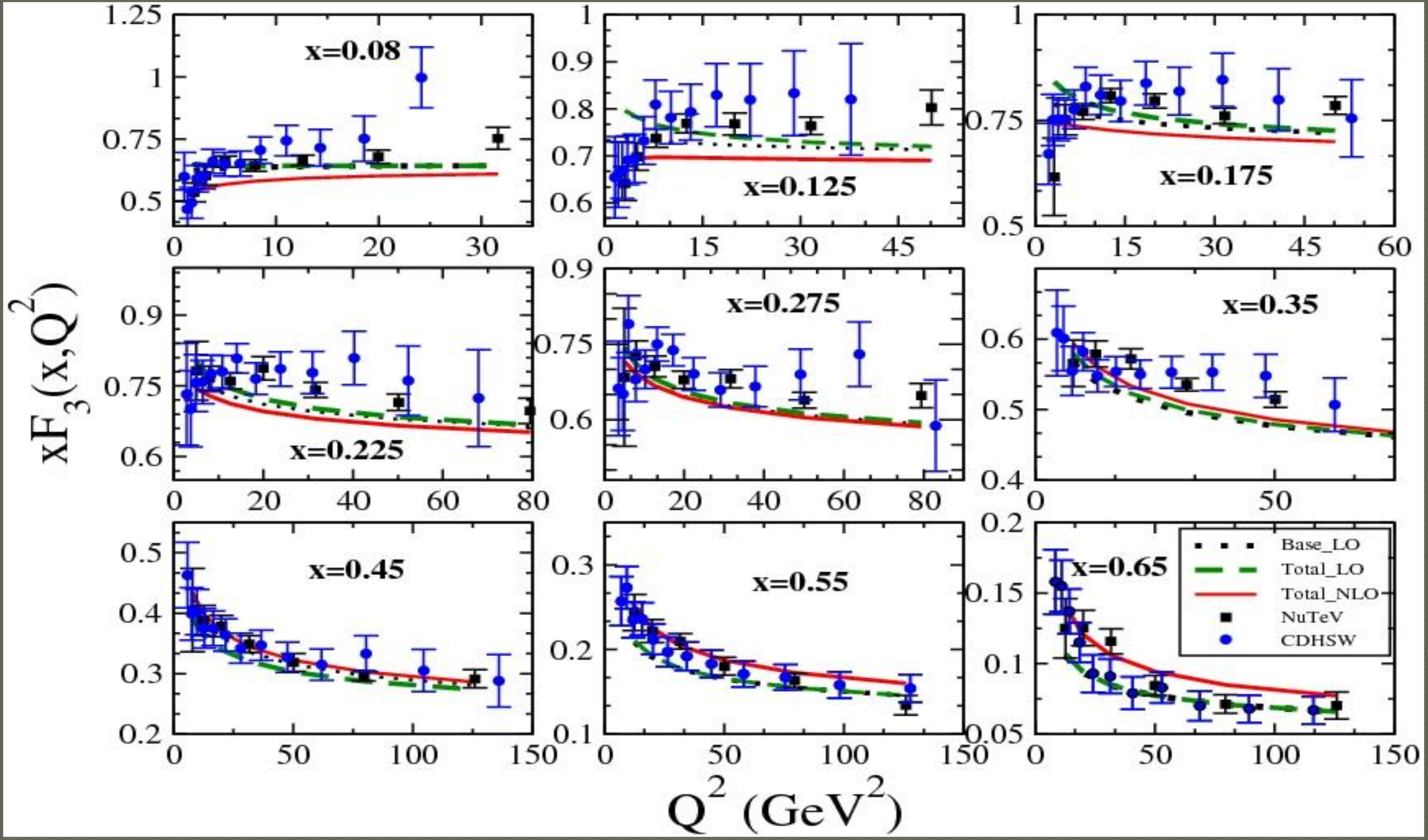
xF_3 vs Q^2 at different values of x in Iron



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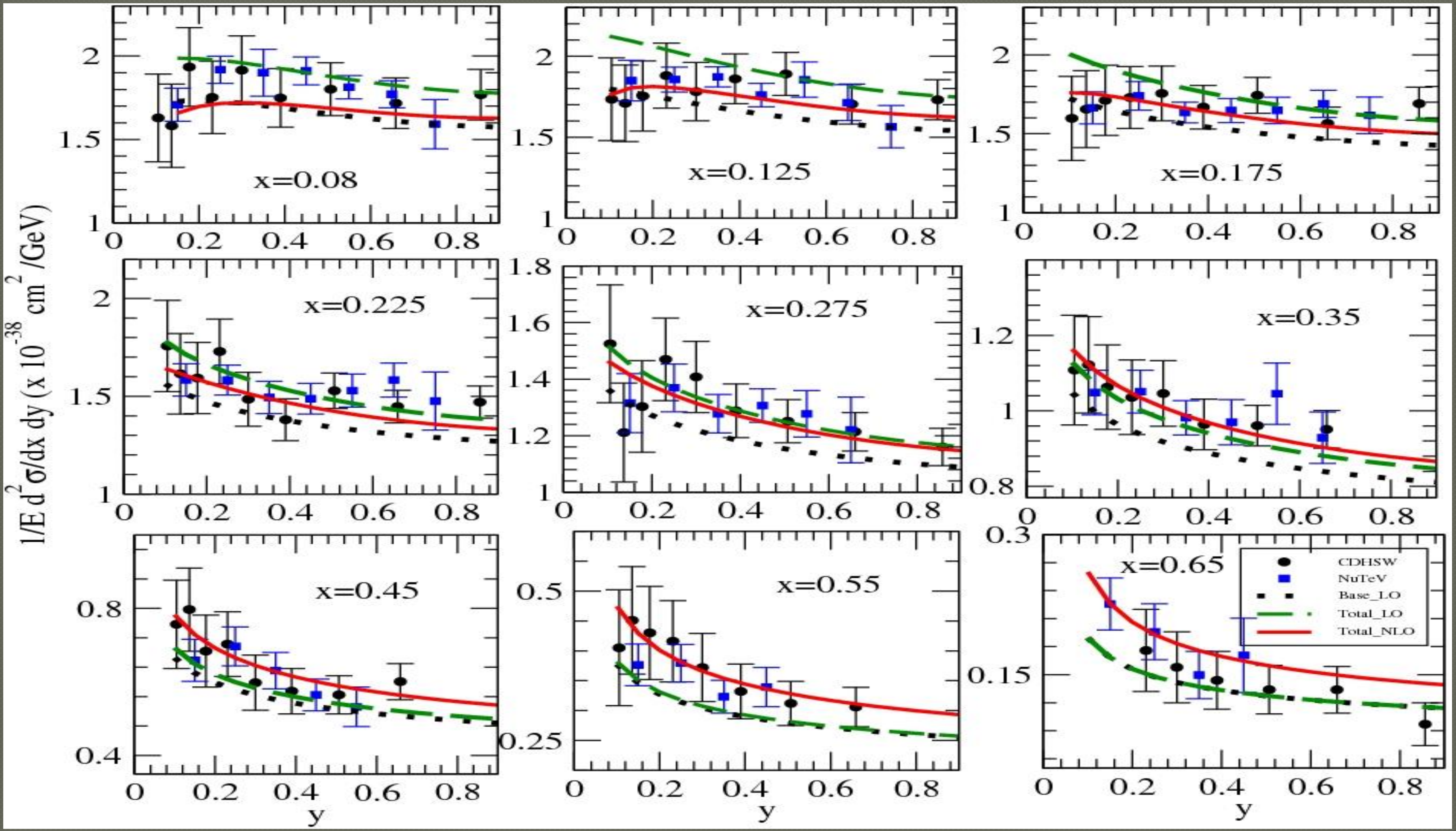
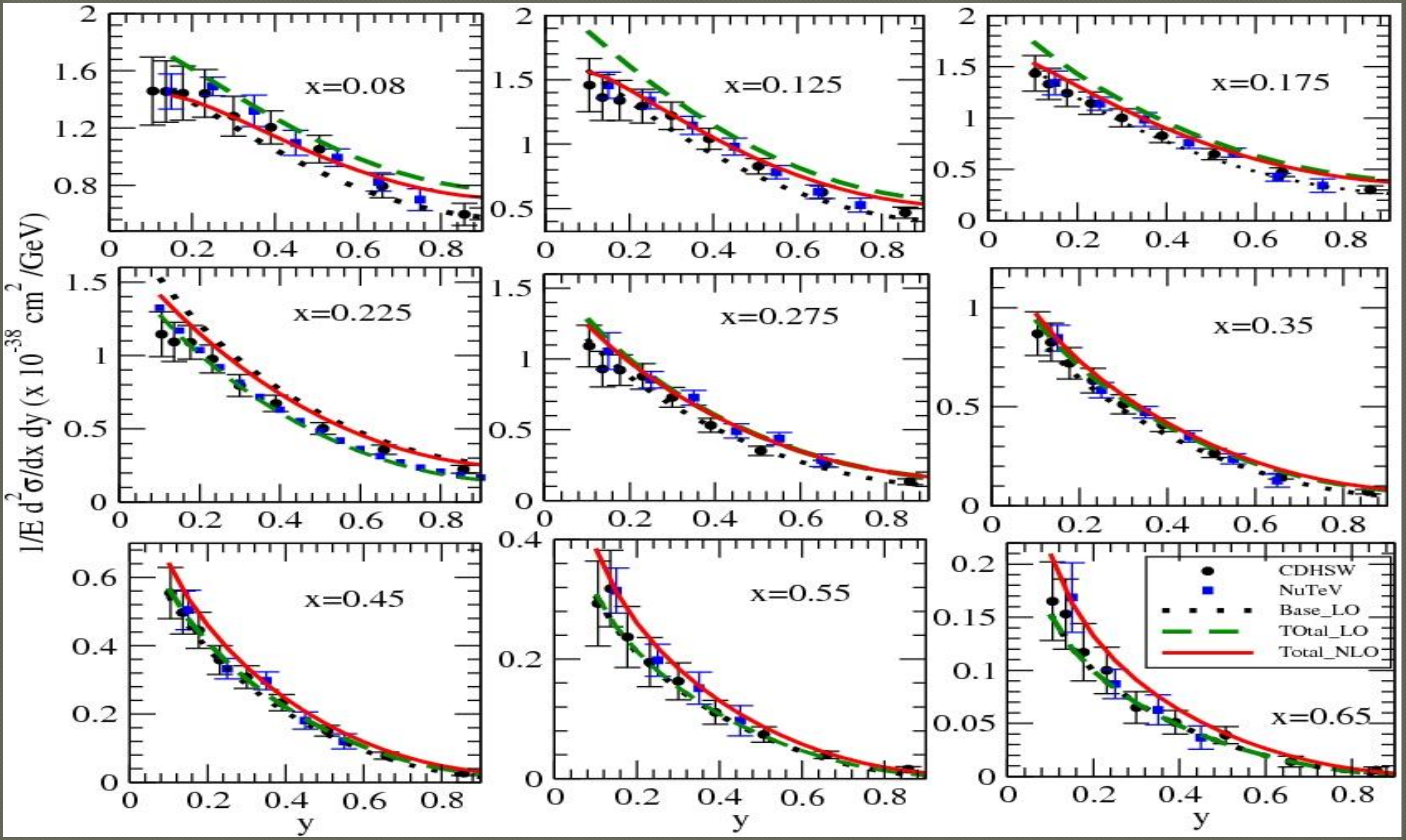
Differential scattering cross section at E=65 GeV for Neutrino case in Iron



PRC 84, 054610 (2011)

Differential scattering cross section at E=65 GeV for Antineutrino case in Iron



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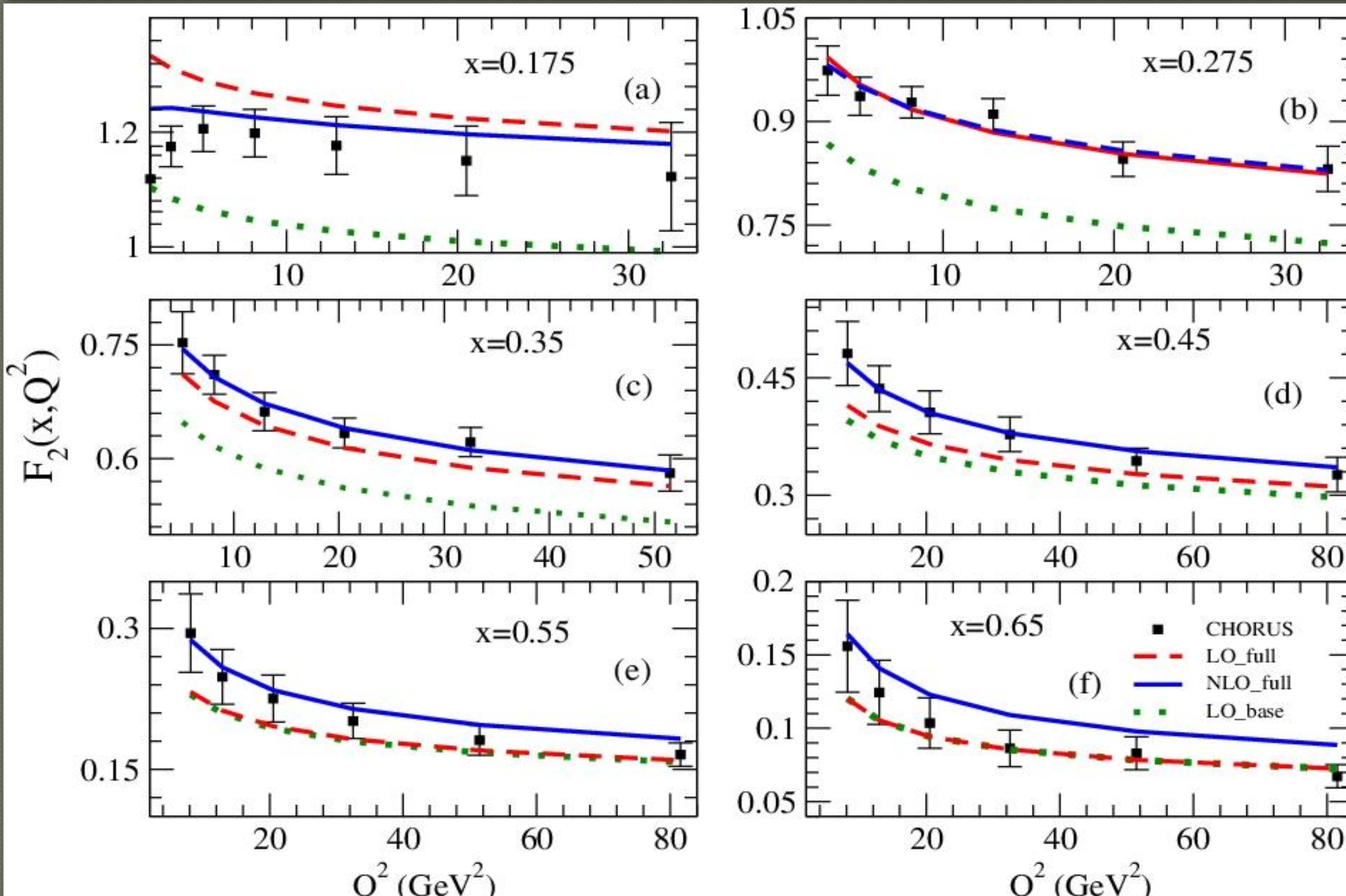
Modified structure functions when target nucleus is treated as nonisoscalar

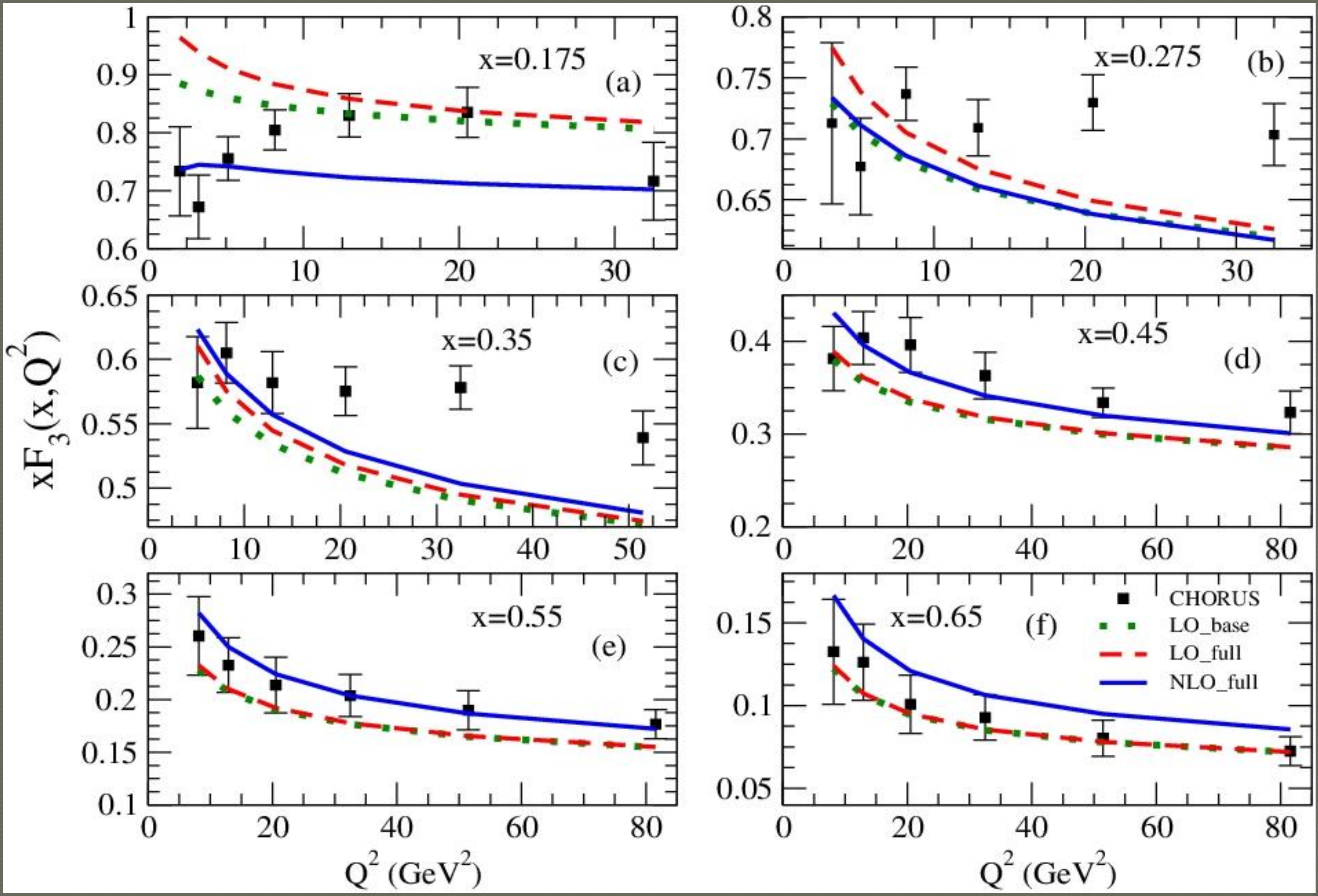
$$
\begin{aligned}
F_2^A(x_A, Q^2) &= 2\int d^3r \int \frac{d^3p}{(2\pi)^3}\,\frac{M}{E(\mathbf{p})}\left[\int_{-\infty}^{\mu_p} dp^0\; S_h^{proton}(p^0, \mathbf{p}, k_{F,p}) F_2^{proton}(x_N, Q^2)\right.\\
&+ \left.\int_{-\infty}^{\mu_n} dp^0\; S_h^{neutron}(p^0, \mathbf{p}, k_{F,n}) F_2^{neutron}(x_N, Q^2)\right]\frac{x}{x_N}\left(1 + \frac{2x_N p_x^2}{M\nu_N}\right)
\end{aligned}
$$

$$
\begin{aligned}
F_3^A(x_A, Q^2) &= 2\int d^3r \int \frac{d^3p}{(2\pi)^3}\,\frac{M}{E(\mathbf{p})}\left[\int_{-\infty}^{\mu_p} dp^0\; S_h^{proton}(p^0, \mathbf{p}, k_{F,p}) F_3^{proton}(x_N, Q^2)\right.\\
&+ \left.\int_{-\infty}^{\mu_n} dp^0\; S_h^{neutron}(p^0, \mathbf{p}, k_{F,n}) F_3^{neutron}(x_N, Q^2)\right]\frac{p^0\gamma - p_z}{(p^0 - p_z\gamma)\gamma}
\end{aligned}
$$

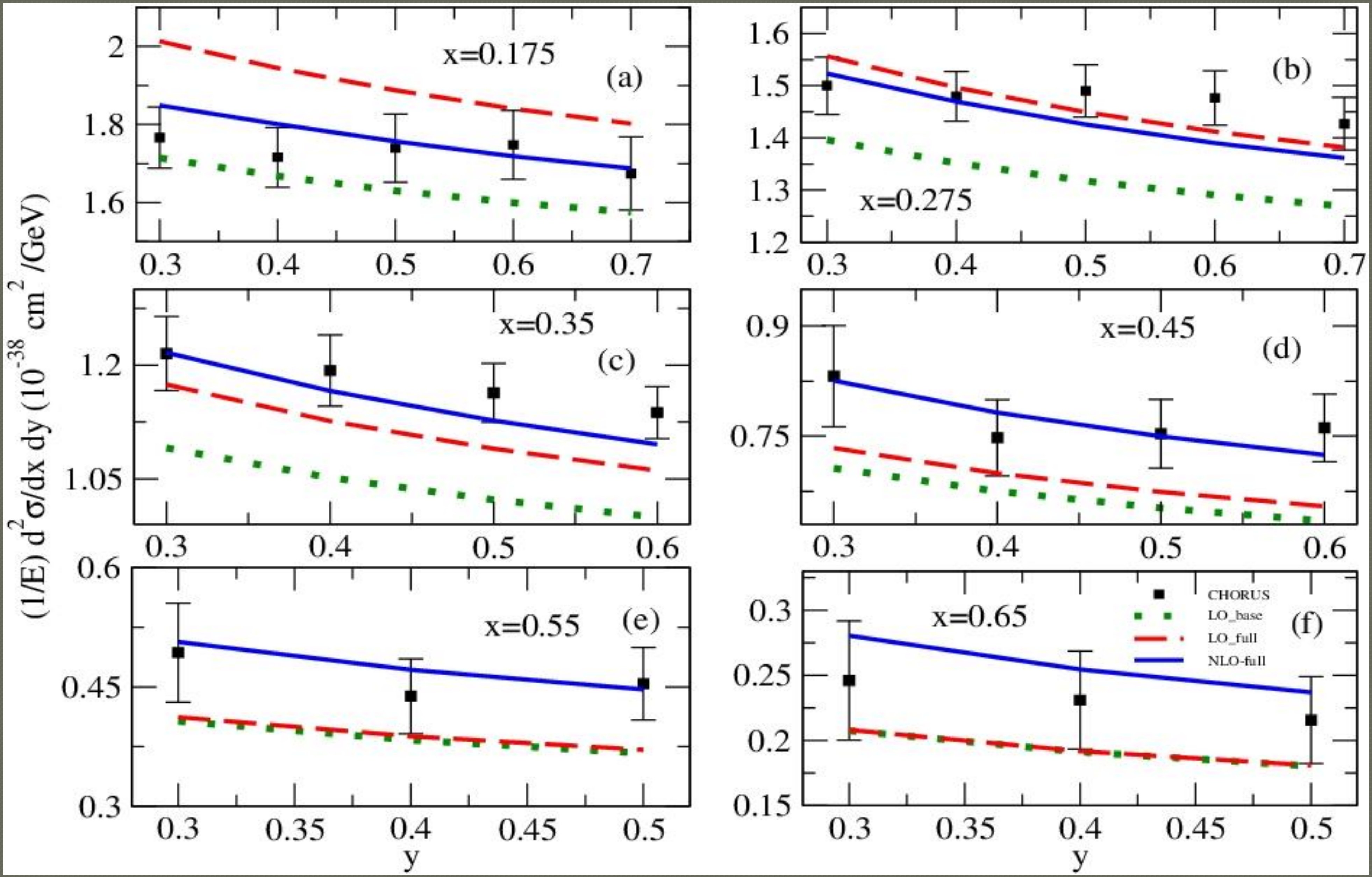
F_2 vs Q^2 at different value of x in Lead



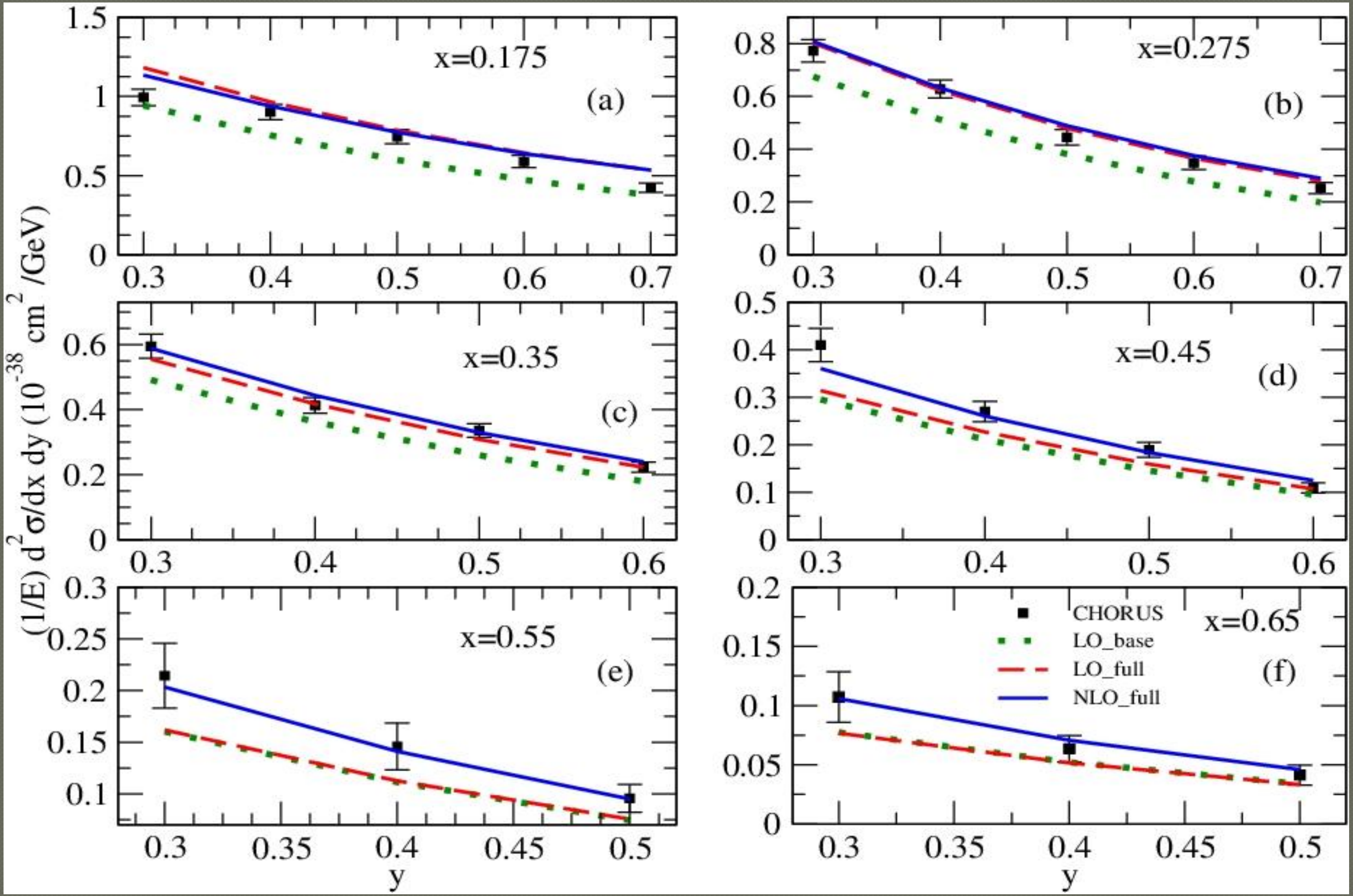
xF_3 vs Q^2 at different value of x in Lead



Differential scattering cross section for Neutrino at E_ν=25 GeV in Lead



Differential scattering cross section for Anti-ν at E_ν=25 GeV in Lead



Conclusions

Total cross section

A. Charged current quasielastic process

The % reduction in the cross section with & without RPA correlations as compared to the cross section calculated for the neutrino – nucleon process is following

E_ν (GeV)	Free Case to Without RPA	Without RPA to With RPA
0.4	18	30
1.0	10	15

B. Charged current incoherent pion production process

E_ν (GeV)	Without ME to With ME	With ME to With ME + Pion Abspn
0.4	40	15
1.5	30	15
3.0	28	12

C. Charged current coherent pion production process

E_ν (GeV)	Without ME to With ME	With ME to With ME + Pion Abspn
0.8	40	50
2.0	24	35
3.0	15	25

Axial Mass dependence

We find that σ increases by about 15% when M_A is changed from 1.05 GeV to 1.21 GeV in the case of CCQE lepton production process as well as in the case of charged current incoherent one pion production process.

Form factor dependence

For the quasielastic process ---- very small change in the peak region of Q^2

For the incoherent one pion production variation is of about 5% in the peak region of Q^2 .

Kaon Production

1. **We have obtained cross sections that are around 2 orders of magnitude smaller than for pion production at the neutrino energies of 1GeV. For antineutrino induced process the contribution is larger than in the case of neutrino.**

2. These cross sections are large enough to be measured in the Minerva and T2K experiments.

3. In the energy region of atmospheric neutrino experiments or in the energy region of 0.8-1.2GeV, the studied processes are the dominant source of Kaons.

DIS

- Nature of $F_2^{EM\,A}/F_2^{EM\,D}$ and $F_2^{W\,A}/F_2^{W\,D}$ are similar, while $F_3^{W\,A}/F_3^{WD}$ is different.

- Nuclear Medium Effects are in better agreement with NuTeV , CDHSW and CHOROUS experimental results.

- Effect of pion and rho cloud contributions are important for x<0.4
  The effect is 16-18% in Carbon, 20-22% in Iron and 22-24% in Lead at x=0.1 which decreases to 6-8% in Iron and Lead at x=0.4.

- Effects of shadowing and anti-shadowing are important for x<0.15
  The effect is 12-14% in Carbon, 20-22% in Iron while it is 22-24% in Lead at x=0.05 which decreases to 6-7% in Iron and Lead at x=0.1.


THANK
YOU!