Possible Ambiguities of Neutrino-Nucleus Scattering in Quasi-elastic Region

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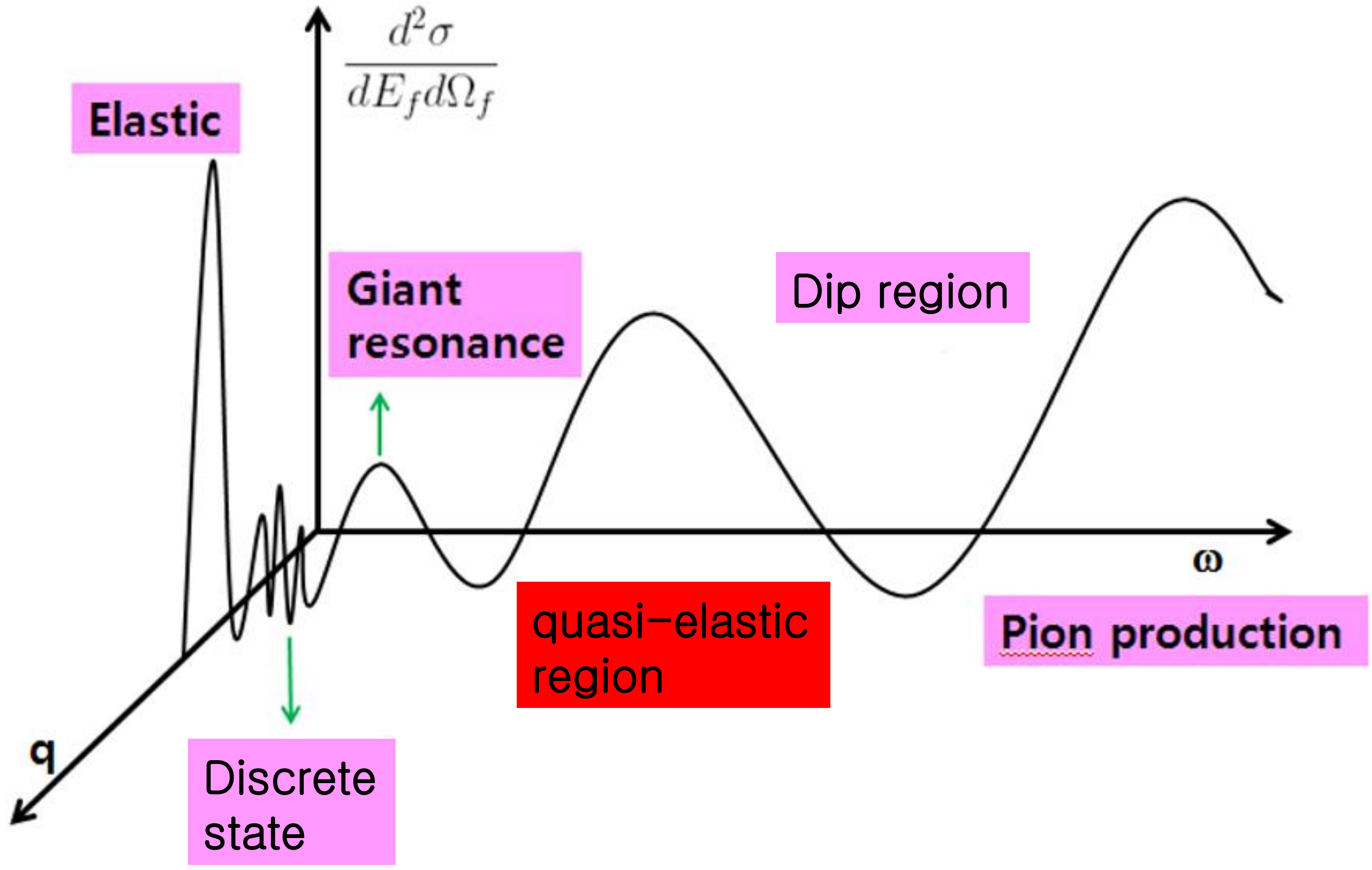
Background

- Since Kamiokande, interests for the neutrino have widely increased.
- Several experiments are running or proposed at BNL, MiniBooNE, and etc.
- With recent developments of a neutrino beam facility, not only neutrino physics, but also hadron physics is closely related to neutrino–nucleus scattering.
- In astrophysics, neutrino–nucleus scattering like $^{12}C(\nu, \nu' n)^{11}C$ reaction during supernova explosions serves as important network processes for light–element nuclear abundances like ^{7}Li and ^{11}B.
- In particular, BNL reported that a value of the strange axial vector form factor of the nucleon does not have a zero value through neutrino scattering.
- Recently, MiniBooNE extracted the different values of axial mass and strange axial form factor.



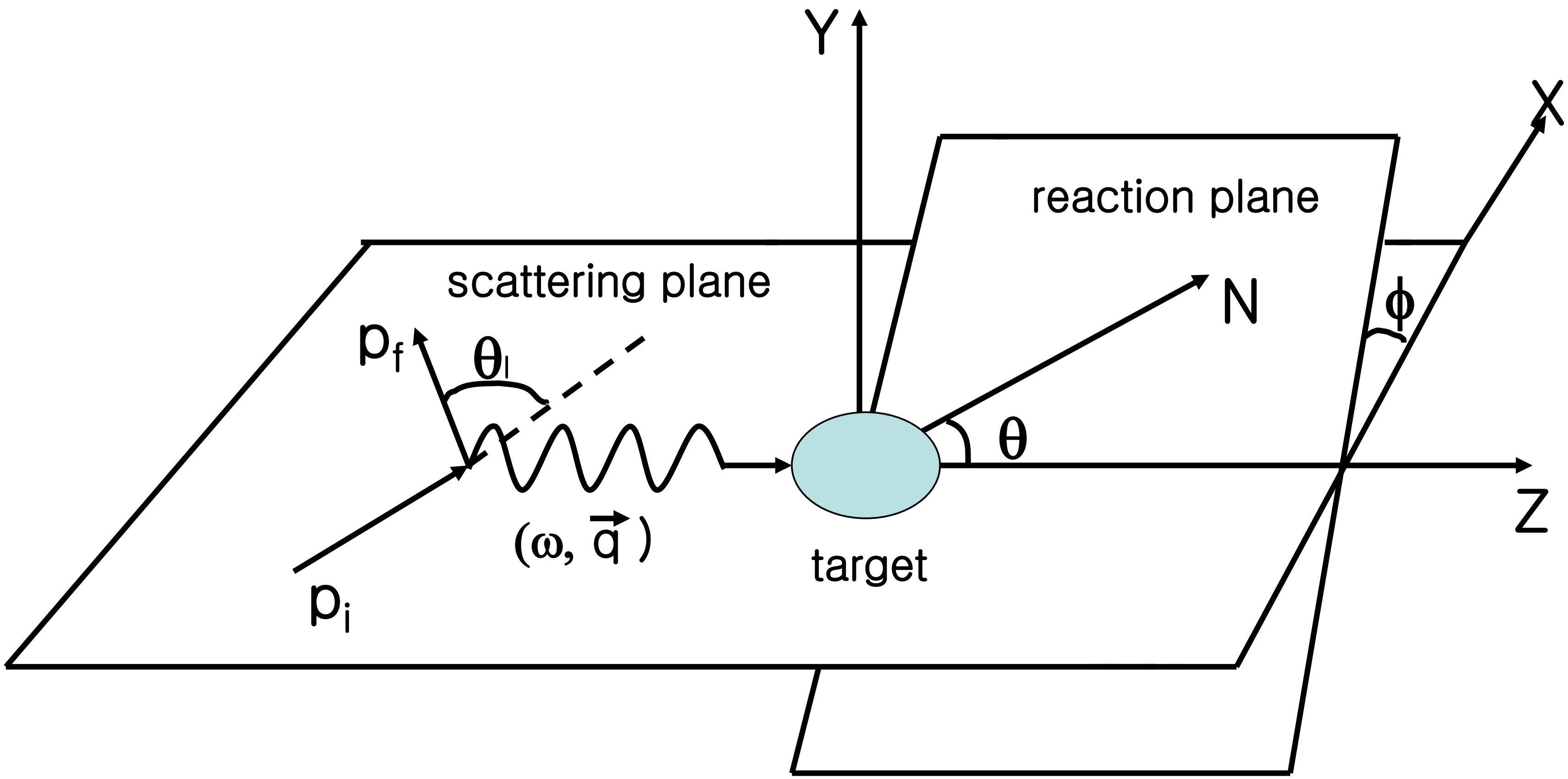
$\frac{d^2\sigma}{dE_f d\Omega_f}$
Elastic
Giant resonance
Dip region
quasi-elastic region
Pion production
Discrete state
ω
q

Ingredients

- Inclusive neutrino-nucleus scattering in quasi-elastic region (no detection of the knocked-out nucleon).
- Use a relativistic single particle model ($\sigma - \omega$ model).
- Investigate the effect of the final state interaction (FSI) of the knocked-out nucleon by using optical and real potentials.
- Investigate the contribution of the strangeness in the axial form factor of weak current.
- Investigate the effects of the proton and neutron emission.
- Study the effect of density-dependence on the weak current.
- Study the asymmetry and the ratios of neutral-current to charged-current.
- Investigate the Coulomb effect of the outgoing lepton for charged-current.

$$\nu(\bar{\nu}) + A \longrightarrow \nu(\bar{\nu}) + N + (A-1)$$ neutral−current (NC) reaction

$$\nu(\bar{\nu}) + A \longrightarrow \ell(\bar{\ell}) + N + (A-1)$$ charged−current (CC) reaction



Motivation :

On the interpretation of the neutrino-nucleus scattering data in the quasi-elastic region, there are several ambiguities: one is medium modification of the nucleon weak form factors, the second one is coming from the final state interaction (FSI) between the knocked-out nucleons and the residual nucleus, and the third one is the contribution of the strange axial form factor and axial mass.

Goal :

Investigate the effect of the density-dependence for medium modification, the strangeness, the axial mass, and the FSI for the neutrino-nucleus scattering .

Formalism

The differential cross section is given by

$$\frac{d\sigma}{dE_f} = \frac{M_N M_{A-1}}{(2\pi)^3 M_A} 4\pi^2 \int \sin\theta_l d\theta_l \int \sin\theta d\theta \times f_{rec}^{-1} p \sigma_M [v_L R_L + v_T R_T + h v_T' R_T']$$

M_N : mass of nucleon

M_{A-1} : mass of residual nucleus

M_A : mass of target nucelus

h : helicity for neutrino (antineutrino)

$p_A^\mu = (E_A, \mathbf{p}_A)$: target nucleus

$p_{A-1}^\mu = (E_{A-1}, \mathbf{p}_{A-1})$: residual nucleus

$p^\mu = (E_p, \mathbf{p})$: knocked-out nucleon

The recoil factor is given by

$$f_{rec} = \frac{E_{A-1}}{M_A} \left| 1 + \frac{E}{E_{A-1}} \left[1 - \frac{\mathbf{q} \cdot \mathbf{p}}{p^2} \right] \right|$$

The kinematic factor $\sigma_M^{Z,W^\pm}$ is defined by

$$\sigma_M^Z = \left(\frac{G_F \cos(\theta_l/2) E_f M_Z^2}{\sqrt{2}\pi (Q^2 + M_Z^2)} \right)^2$$ NC reaction

$$\sigma_M^{W^\pm} = \sqrt{1 - \frac{M_l^2}{E_f}} \left(\frac{G_F \cos(\theta_C) E_f M_W^2}{2\pi (Q^2 + M_W^2)} \right)^2$$ CC reaction

M_Z and M_W: mass of Z– and W–boson

θ_l: scattering angle $\cos^2\theta_C \simeq 0.9749$: Cabibbo angle

For the NC reaction, the kinematic factors are given by

$$v_L = 1 \qquad v_T = \tan^2\frac{\theta_l}{2} + \frac{Q^2}{2q^2} \qquad v_T' = \tan\frac{\theta_l}{2}\left[\tan^2\frac{\theta_l}{2} + \frac{Q^2}{q^2}\right]^{1/2}$$

The response functions are given by

$$R_L = \left| J^0 - \frac{\omega}{q} J^z \right|^2 \qquad R_T = |J^x|^2 + |J^y|^2 \qquad R_T' = 2\mathrm{Im}(J^{x*} J^y)$$

For the CC reaction, the kinematics factors are given by

$$v_L^0 = 1 + \sqrt{1 - \frac{M_l^2}{E_f^2}} \cos\theta_l \quad v_L^z = 1 + \sqrt{1 - \frac{M_l^2}{E_f^2}} \cos\theta_l - \frac{2E_iE_f}{q^2}\left(1 - \frac{M_l^2}{E_f^2}\right)\sin^2\theta_l$$

$$v_L^{0z} = \frac{\omega}{q}\left(1 + \sqrt{1 - \frac{M_l^2}{E_f^2}} \cos\theta_l\right) + \frac{M_l^2}{E_f q}$$

$$v_T = 1 - \sqrt{1 - \frac{M_l^2}{E_f^2}} \cos\theta_l + \frac{E_iE_f}{q^2}\left(1 - \frac{M_l^2}{E_f^2}\right)\sin^2\theta_l \quad v_T' = \frac{E_i + E_f}{q}\left(1 - \sqrt{1 - \frac{M_l^2}{E_f^2}} \cos\theta_l\right) - \frac{M_l^2}{E_f q}$$

and corresponding response functions are given by

$$R_L^0 = |J^0|^2 \qquad R_L^z = |J^z|^2 \qquad R_L^{0z} = -2\mathrm{Re}(J^0 J^{z*})$$

$$R_T = |J^x|^2 + |J^y|^2 \qquad R_T' = 2\mathrm{Im}(J^x J^{y*})$$

with $v_L R_L = v_L^0 R_L^0 + v_L^z R_L^z + v_L^{0z} R_L^{0z}$

The total cross section $\sigma = \int \frac{d\sigma}{dT_p} dT_p$

T_p : kinetic energy of knocked-out nucleon

The relativistic nucleon weak current operator

$$J^\mu = F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M_N}F_2(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 + \frac{1}{2M_N}G_P(Q^2)q^\mu\gamma_5$$

weak vector form factors

$$F_i^{V,\ p(n)} = (\frac{1}{2} - 2\sin^2\theta_W)F_i^{p(n)} - \frac{1}{2}F_i^{n(p)} - \frac{1}{2}F_i^s$$

$$F_1^s(Q^2) = \frac{F_1^s Q^2}{(1+\tau)(1+Q^2/M_V^2)^2} \qquad \tau = Q^2/(4M_N^2)$$

$$F_2^s(Q^2) = \frac{F_2^s(0)}{(1+\tau)(1+Q^2/M_V^2)^2} \qquad M_V = 0.843\ \mathrm{GeV}$$

$$F_1^s = - < r_s^2 > /6 = 0.53\ \mathrm{GeV}^{-2}$$

$F_2^s(0) = \mu_s = -0.4$ strange magnetic moment

$$G_A = \frac{1}{2}(\mp g_A + g_A^s)G$$: axial form factor

$$G_P(Q^2) = \frac{2M_N}{Q^2 + m_\pi^2} G_A(Q^2)$$: pseudoscalar form factor disappear for NC reaction

$$g_A = 1.262$$

$$g_A^s = -0.19$$

$$\sin^2\theta_W = 0.2224$$: Weinberg angle

$$G = (1 + Q^2/M_A^2)^{-2}$$ with M_A =1.032 GeV

Strange magnetic moment

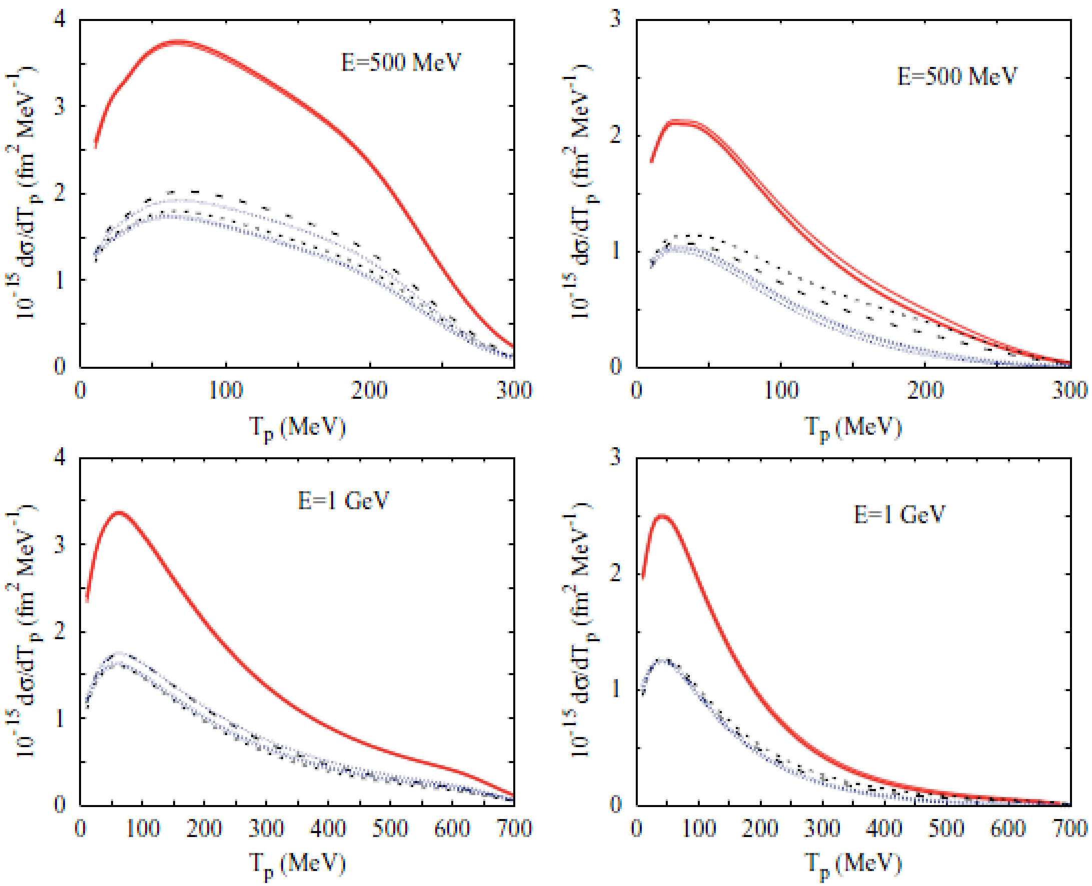
Ref : PRC 77, 054604 (2008)

thick : $\mu_s = -0.4$

thin : $\mu_s = 0.4$

$^{12}\mathrm{C}(\nu, \nu')$

$^{12}\mathrm{C}(\bar{\nu}, \bar{\nu}')$



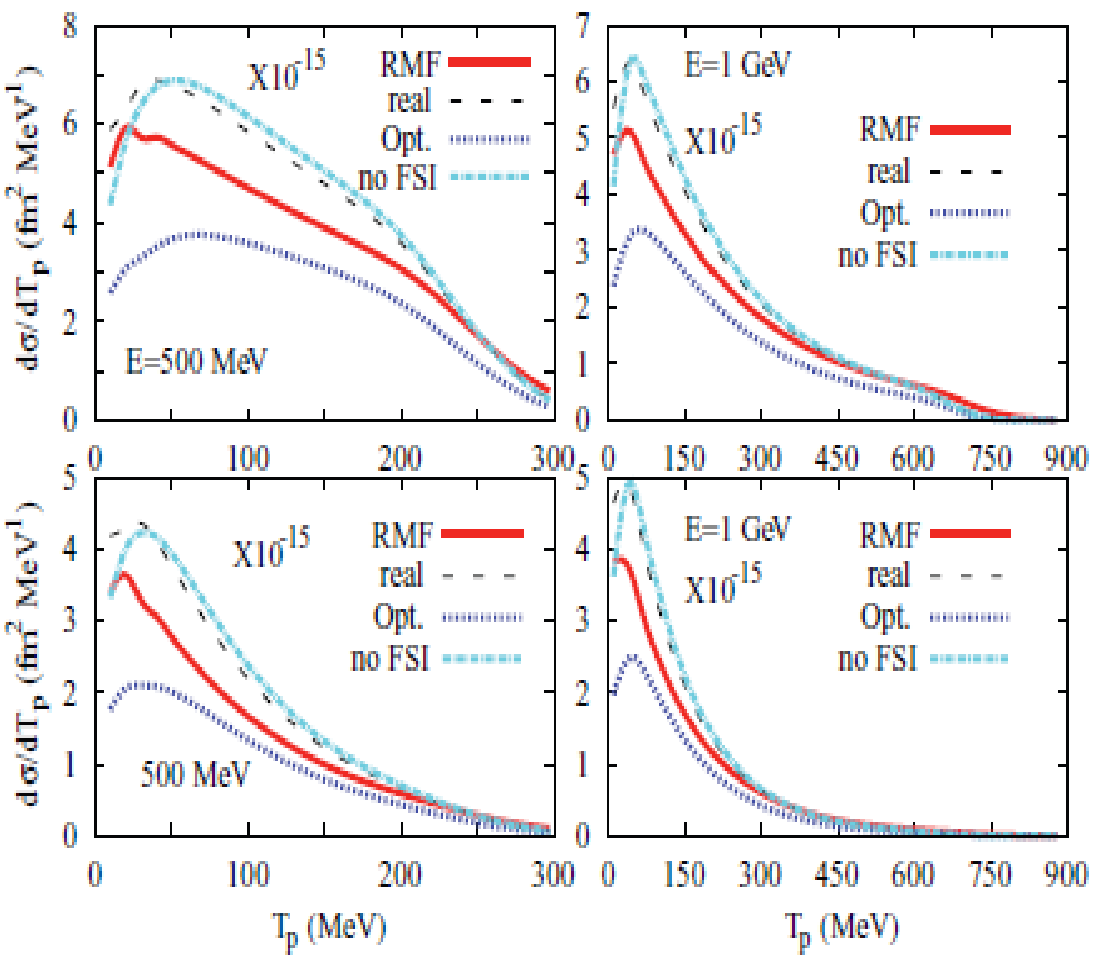
red (solid): differential cross section

black (dash) : knocked-out proton

blue (dot) : knocked-out neutron

FSI

RMF : use the same potential of the bound nucleon
for final nucleon
Opt. : optical potential
real : real part of optical potential
no FSI : plane wave

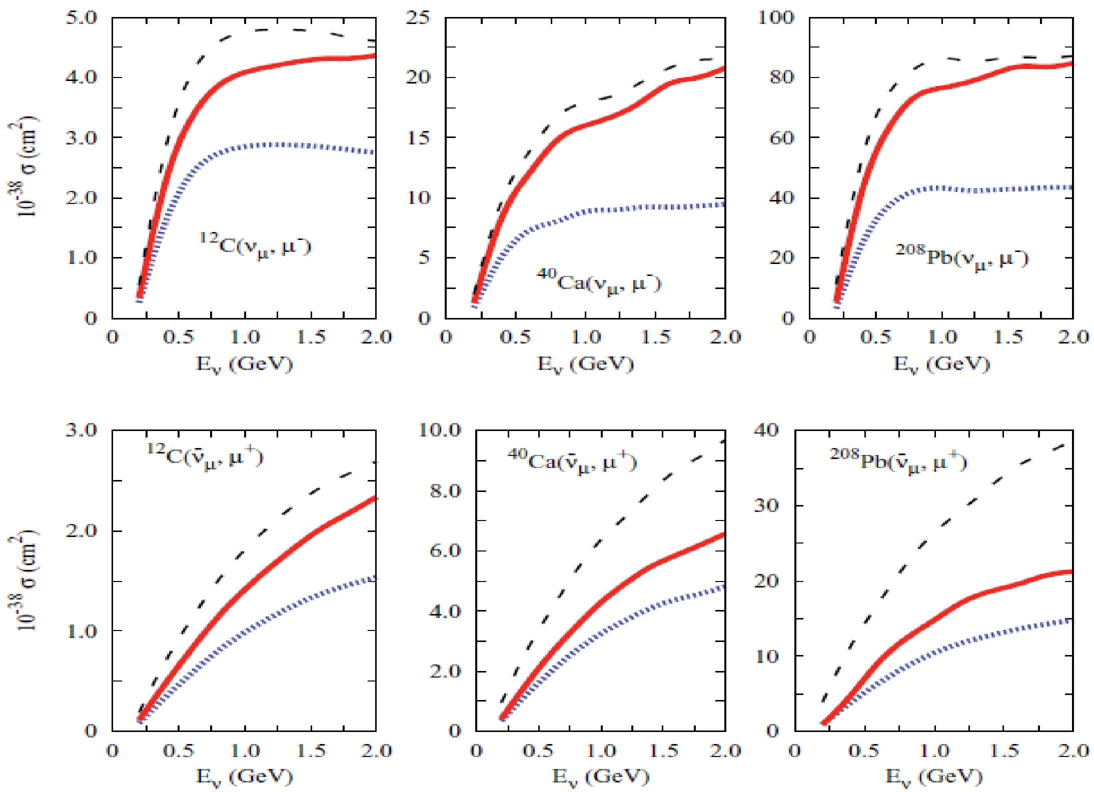


Ref : PRC 88, 044615 (2013)

$^{12}\mathrm{C}(\nu, \nu')$

$^{12}\mathrm{C}(\bar{\nu}, \bar{\nu}')$

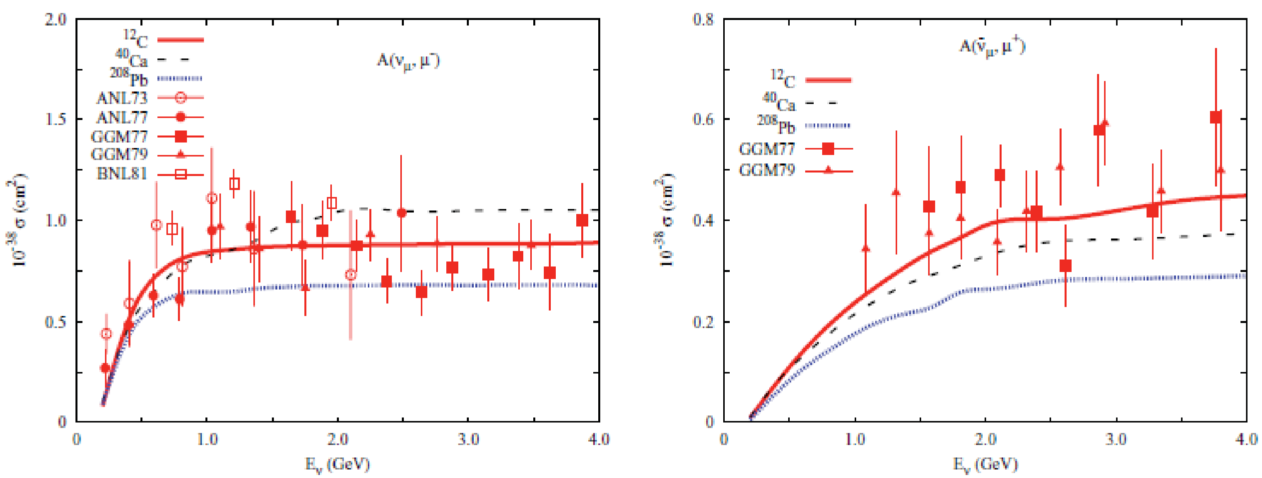
Ref : PRC 88, 044615 (2013)



RMF

no FSI

optical

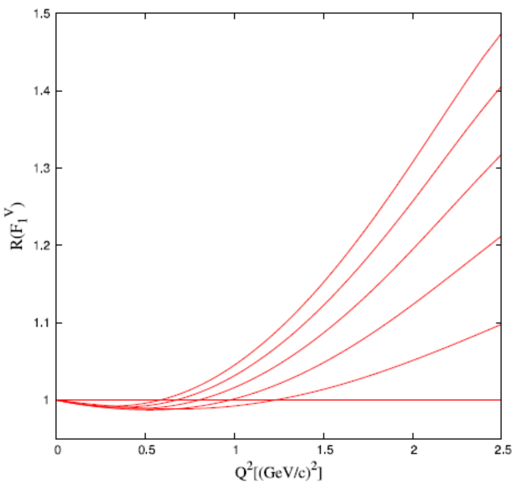


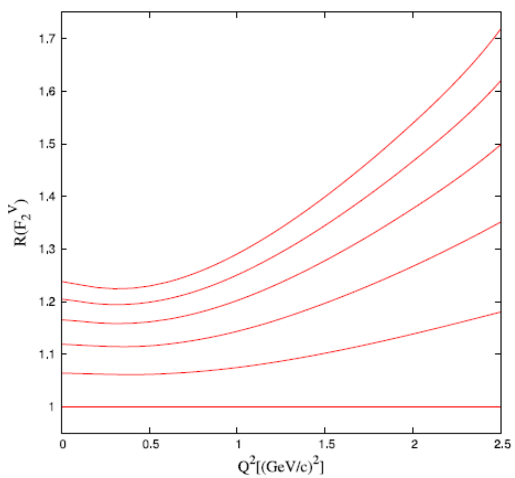
only RMF

Density-dependence weak form factor

obtained from QMC model at Adelaide group

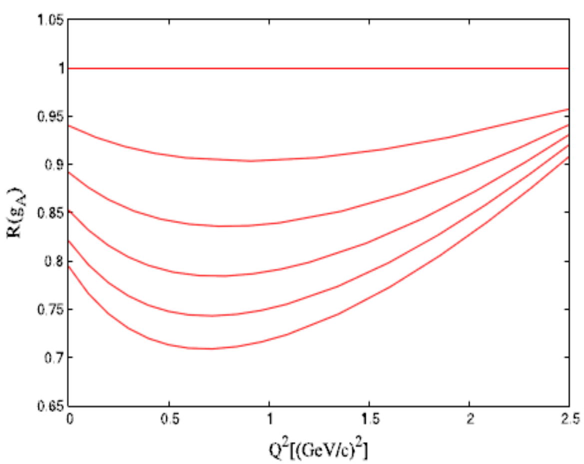
Refs : Phys. Lett. B 417, 217 (1998),
Phys. Rev. C 60 068201 (1999)





$$R(F^V_{1,2}) = F^V_{1,2}(\rho, Q^2)/F^V_{1,2}(\rho = 0, Q^2)$$

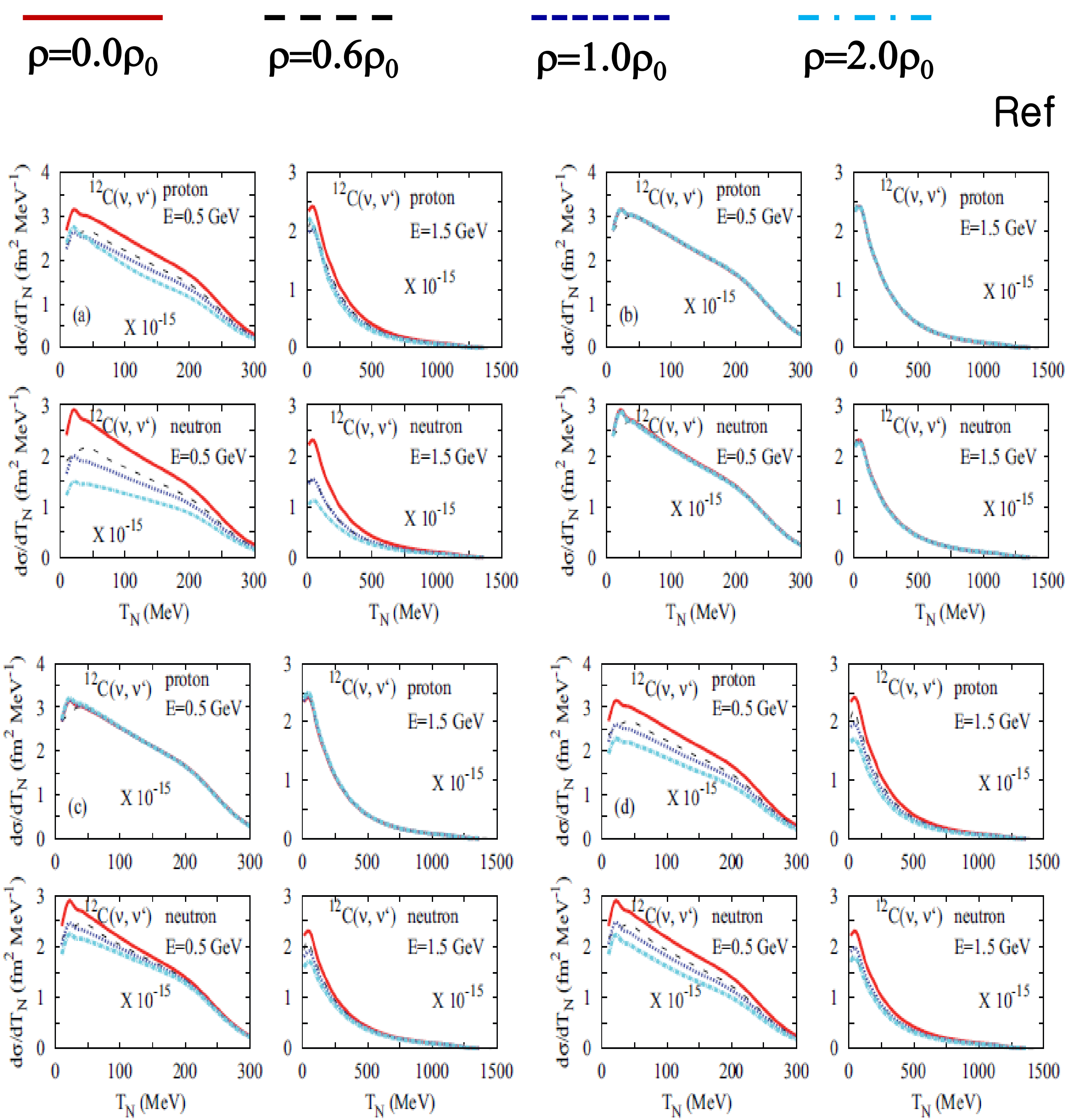
From the lowermost (for vacuum),
the density increases by $0.5\rho_0$ in order.
The uppermost curve is for$\rho=2.5\rho_0$.



$$R(g_A) = g_A(\rho, Q^2)/g_A(\rho = 0, Q^2)$$

From the uppermost (for vacuum), the density increases
by $0.5\rho_0$ in order.
The lowermost curve is for $\rho=2.5\rho_0$.

Ref : PRC 91, 014606 (2015)



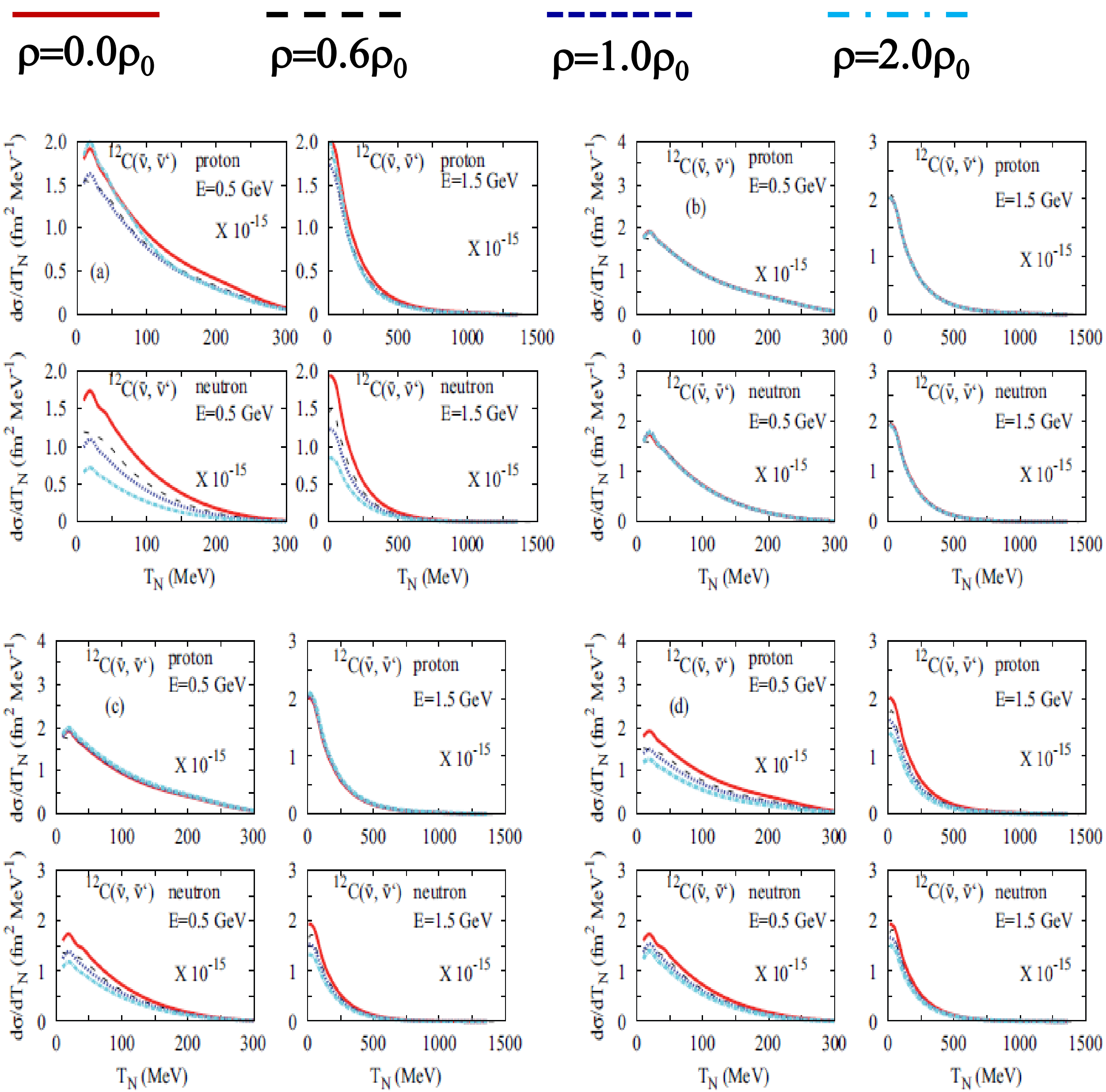
(a) density-dependence of all form factors (F_1, F_2, g_A).

(b) density-dependence of only F_1.

(c) density-dependence of only F_2.

(d) density-dependence of only g_A.

Ref : PRC 91, 014606 (2015)



(a) density-dependence of all form factors (F_1, F_2, g_A).

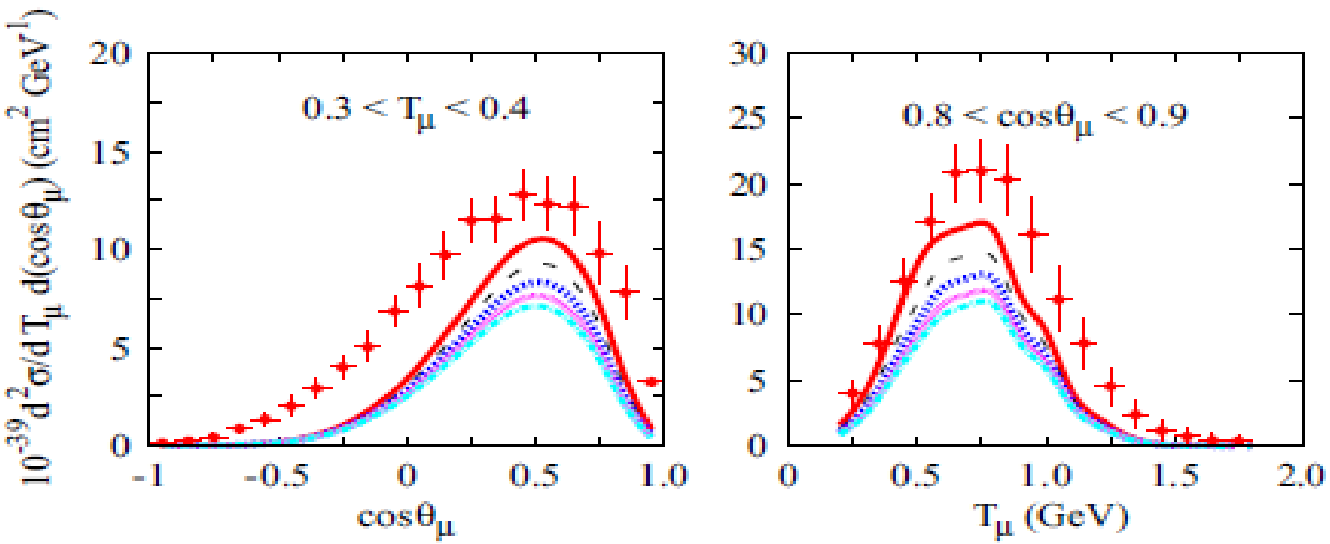
(b) density-dependence of only F_1.

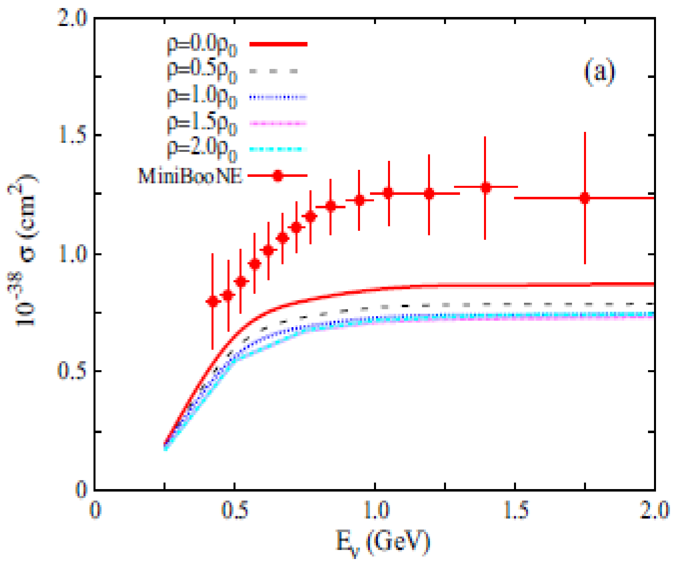
(c) density-dependence of only F_2.

(d) density-dependence of only g_A.

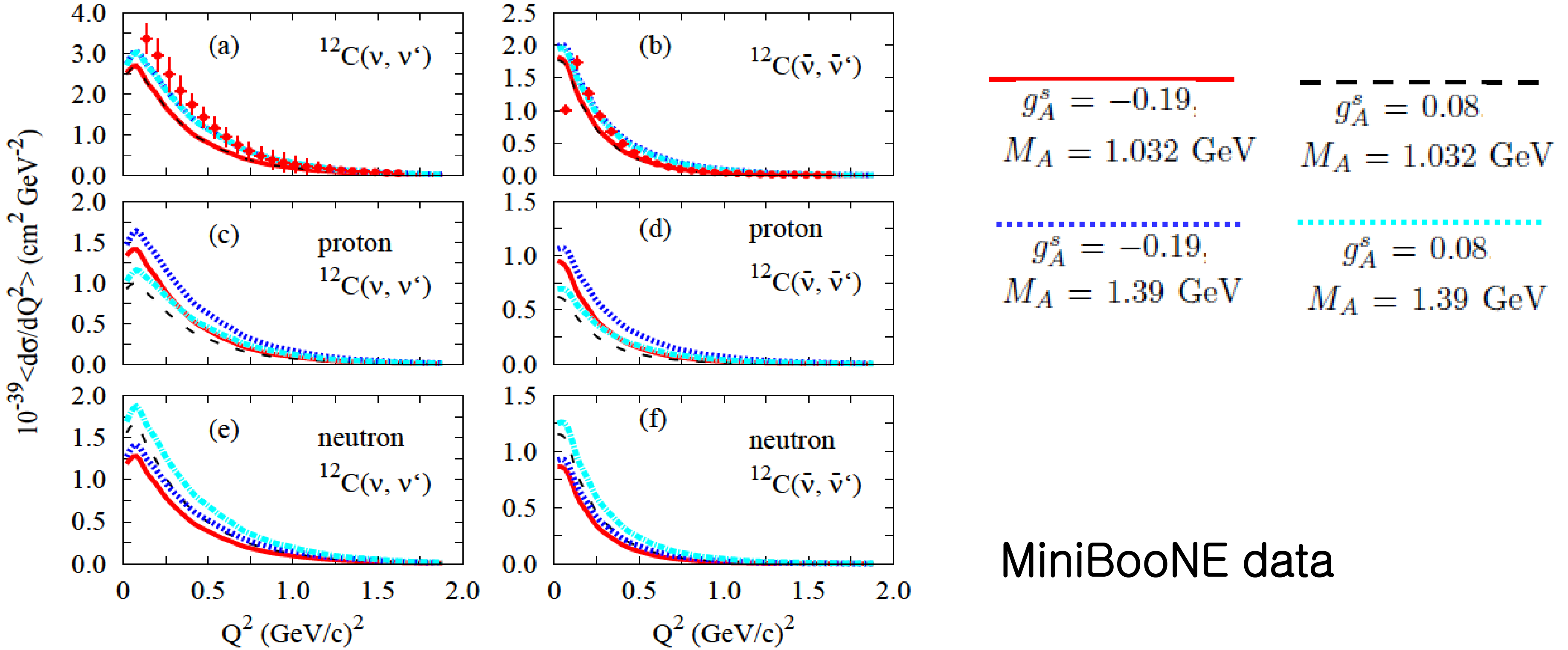
$^{12}C(\nu_\mu, \mu^-)$ reaction

Ref：PRC 90, 017601 (2014)

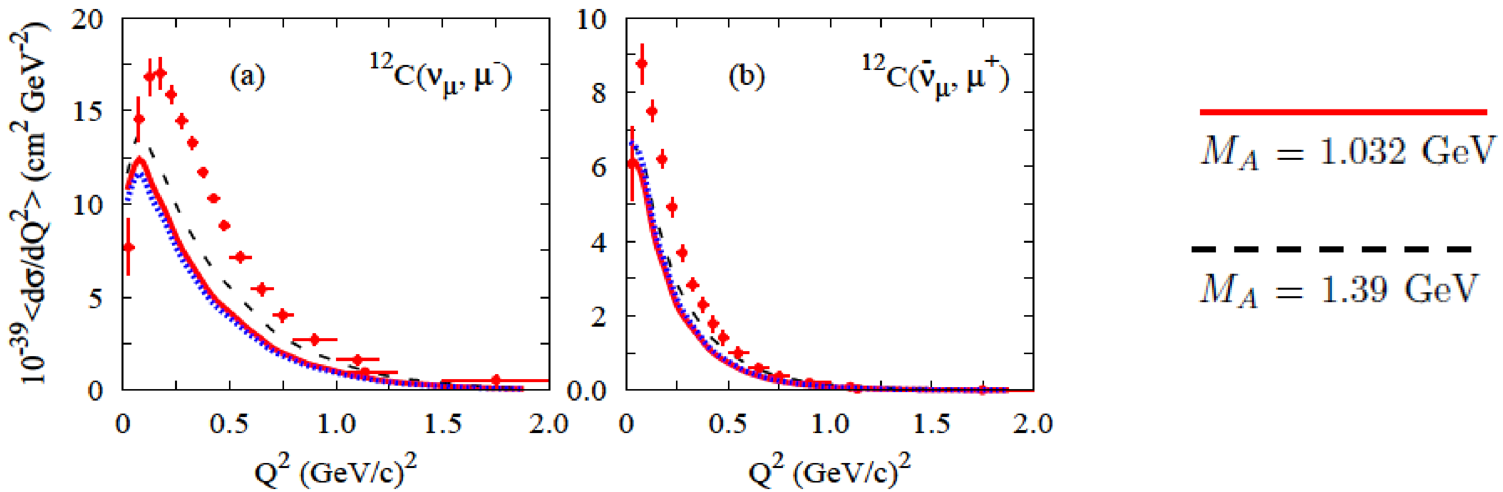




Effect of strange axial form factor and axial mass



MiniBooNE data



Response cross sections

$g_A^s = -0.19$, $M_A = 1.032$ GeV

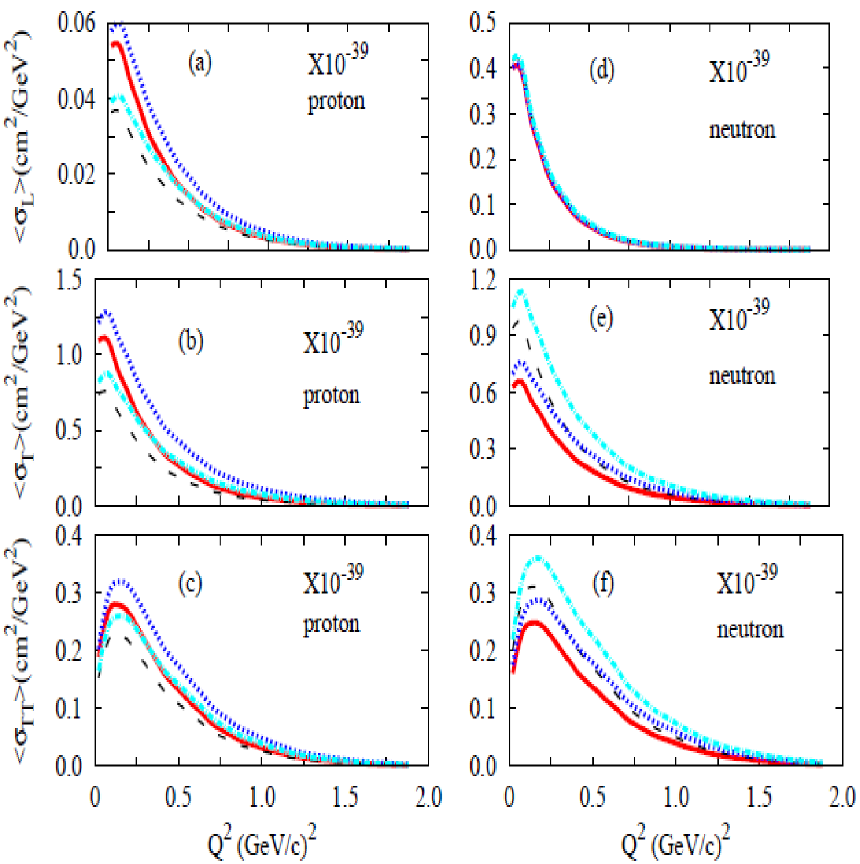
$g_A^s = 0.08$, $M_A = 1.032$ GeV

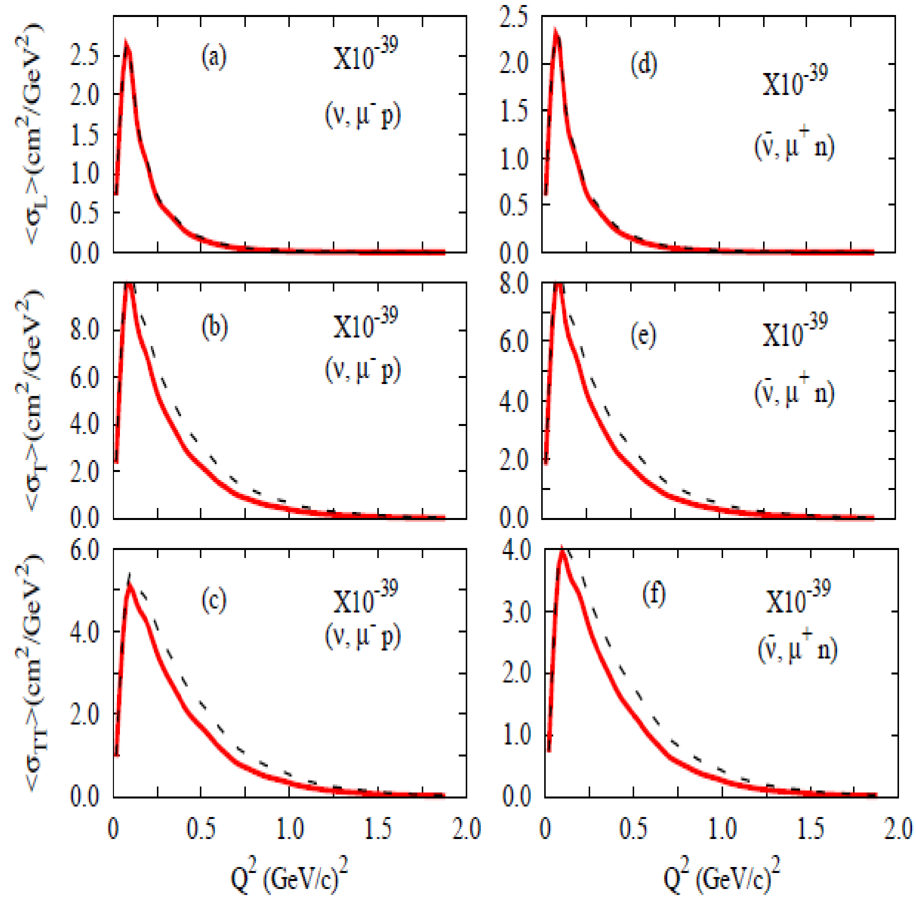
$g_A^s = -0.19$, $M_A = 1.39$ GeV

$g_A^s = 0.08$, $M_A = 1.39$ GeV

$M_A = 1.032$ GeV

$M_A = 1.39$ GeV





Asymmetry

$$A_{NC} = \frac{\sigma(\nu) - \sigma(\bar{\nu})}{\sigma(\nu) + \sigma(\bar{\nu})}$$

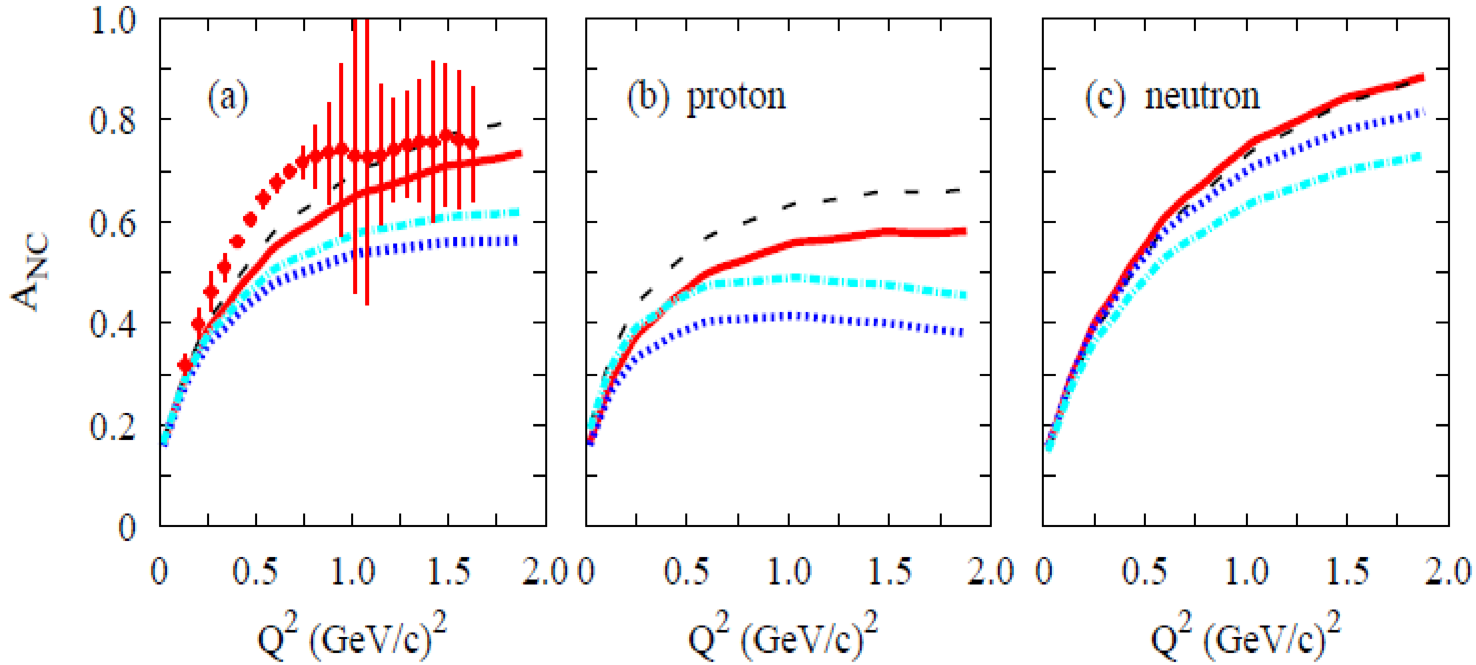
$g_A^s = -0.19$, $M_A = 1.032$ GeV

$g_A^s = 0.08$, $M_A = 1.032$ GeV

$g_A^s = -0.19$, $M_A = 1.39$ GeV

$g_A^s = 0.08$, $M_A = 1.39$ GeV

MiniBooNE data



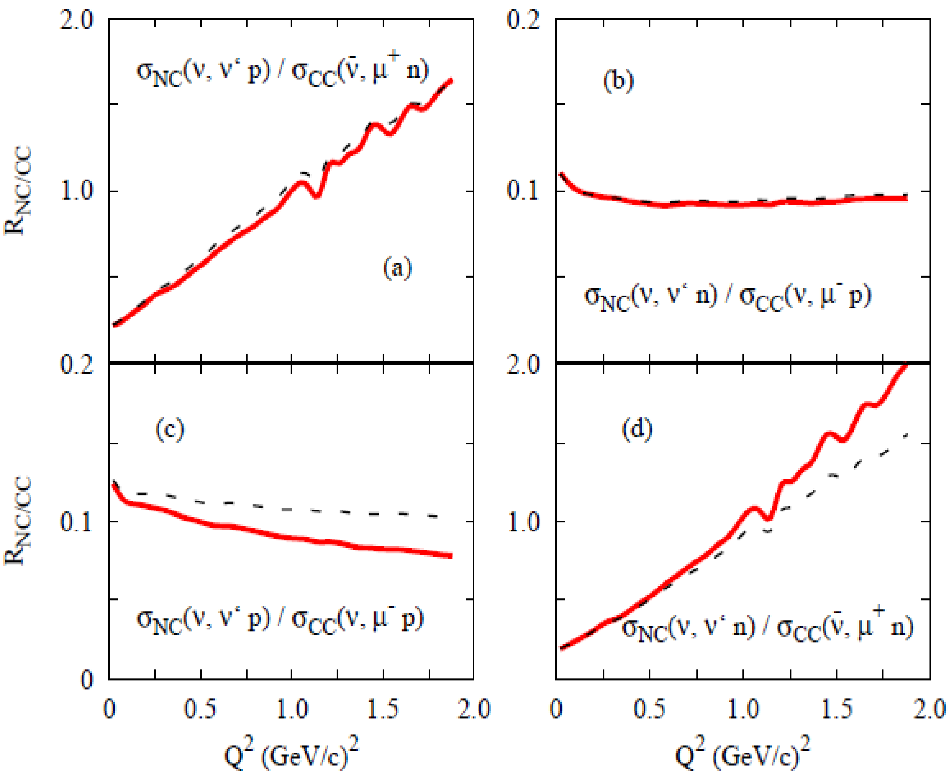
Ratios

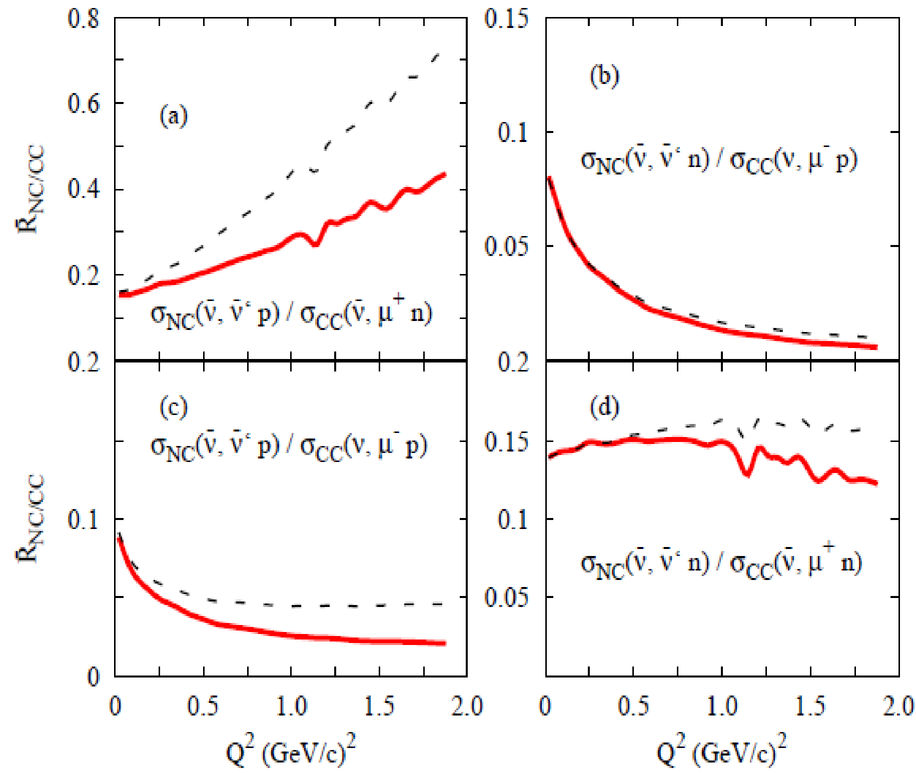
$$R_{NC/CC} = \frac{\sigma_{NC}(\nu,\nu'\,p)}{\sigma_{CC}(\bar{\nu},\mu^+\,n)}$$
$$\text{or} = \frac{\sigma_{NC}(\nu,\nu'\,n)}{\sigma_{CC}(\nu,\mu^-\,p)}$$
$$\text{or} = \frac{\sigma_{NC}(\nu,\nu'\,p)}{\sigma_{CC}(\nu,\mu^-\,p)}$$
$$\text{or} = \frac{\sigma_{NC}(\nu,\nu'\,n)}{\sigma_{CC}(\bar{\nu},\mu^+\,n)}$$

$M_A = 1.032$ GeV

$M_A = 1.39$ GeV

$$\bar{R}_{NC/CC} = \frac{\sigma_{NC}(\bar{\nu},\bar{\nu}'\,p)}{\sigma_{CC}(\bar{\nu},\mu^+\,n)}$$
$$\text{or} = \frac{\sigma_{NC}(\bar{\nu},\bar{\nu}'\,n)}{\sigma_{CC}(\nu,\mu^-\,p)}$$
$$\text{or} = \frac{\sigma_{NC}(\bar{\nu},\bar{\nu}'\,p)}{\sigma_{CC}(\nu,\mu^-\,p)}$$
$$\text{or} = \frac{\sigma_{NC}(\bar{\nu},\bar{\nu}'\,n)}{\sigma_{CC}(\bar{\nu},\mu^+\,n)}$$





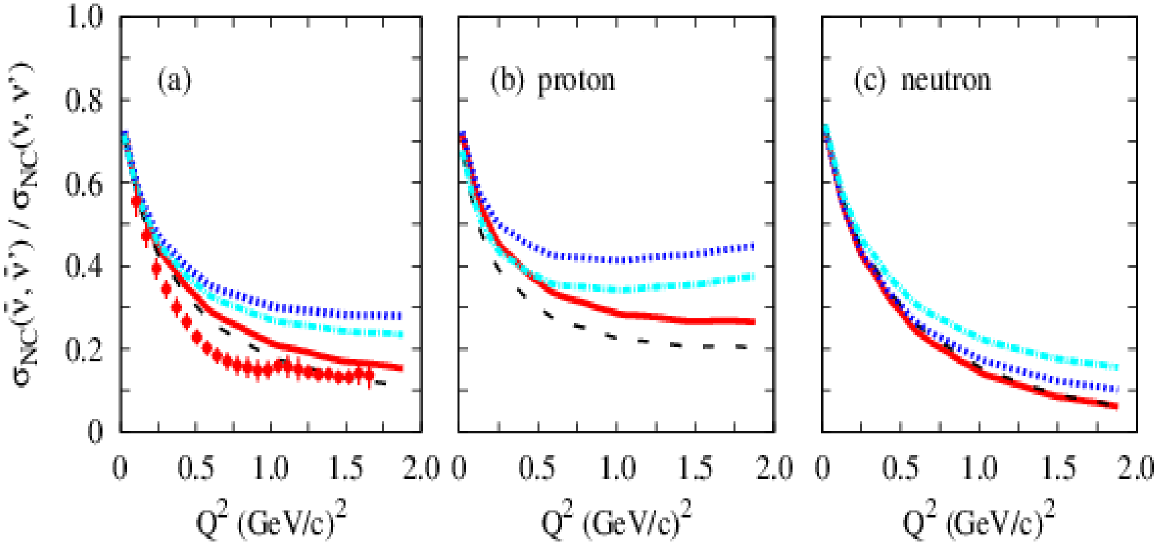
$$\frac{\sigma_{NC}(\overline{\nu}, \overline{\nu}')}{\sigma_{NC}(\nu, \nu')}$$

$g_A^s = -0.19$, $M_A = 1.032$ GeV

$g_A^s = 0.08$, $M_A = 1.032$ GeV

$g_A^s = -0.19$, $M_A = 1.39$ GeV

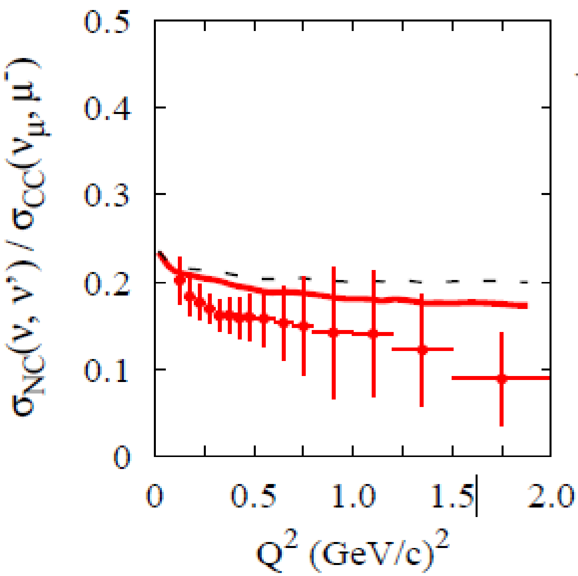
$g_A^s = 0.08$, $M_A = 1.39$ GeV

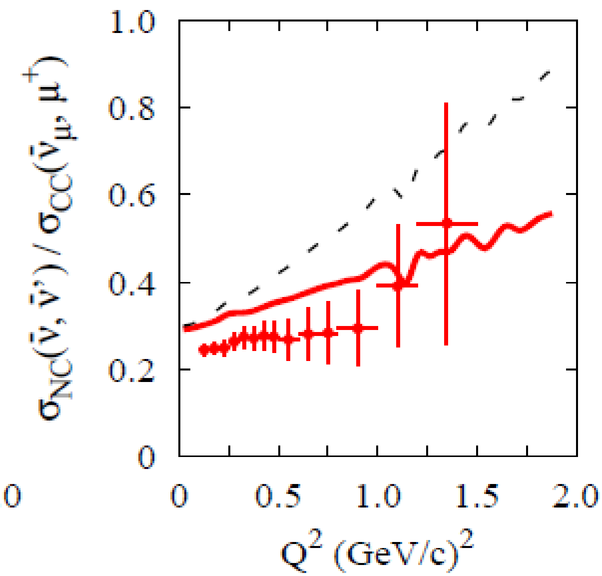


$$\frac{\sigma_{NC}(\nu, \nu')}{\sigma_{CC}(\nu_\mu, \mu^-)}$$

$$\frac{\sigma_{NC}(\overline{\nu}, \overline{\nu}')}{\sigma_{CC}(\overline{\nu}_\mu, \mu^+)}$$

MiniBooNE data





$M_A = 1.032$ GeV

$M_A = 1.39$ GeV

Coulomb Effect

Ref. : PRC 60, 067604 (1999)

Approximate electron wave functions are given by

$$\Psi^{\pm}(\mathbf{r}) = \frac{p'(r)}{p} \; e^{\pm i\delta(\mathbf{L}^2)} \; e^{i\Delta} \; e^{i\mathbf{p}'(r)\cdot\mathbf{r}} \; u_p$$

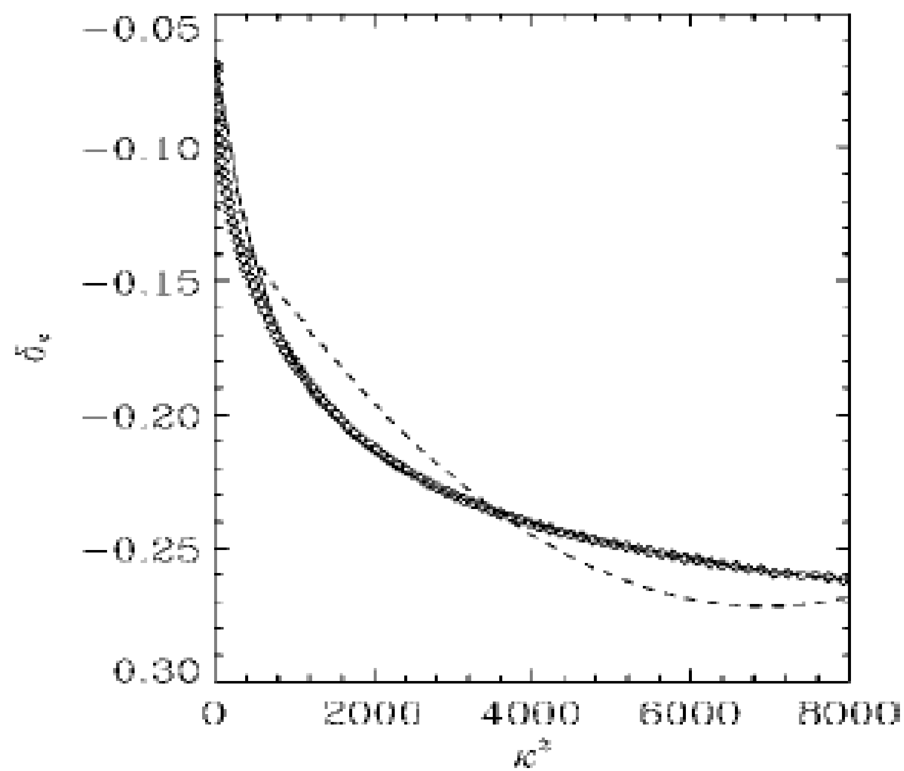
$$\mathbf{p}'(\mathbf{r}) = \left(p - \frac{1}{r}\int_0^r V(r)\,dr \right)\hat{\mathbf{p}}$$

local effective momentum approximation (LEMA)

$$\Delta = a[\hat{\mathbf{p}}'(r)\cdot\hat{r}]\mathbf{L}^2$$

$$a = -\alpha Z[(16 \;\; \mathrm{MeV}/c)/p]^2$$

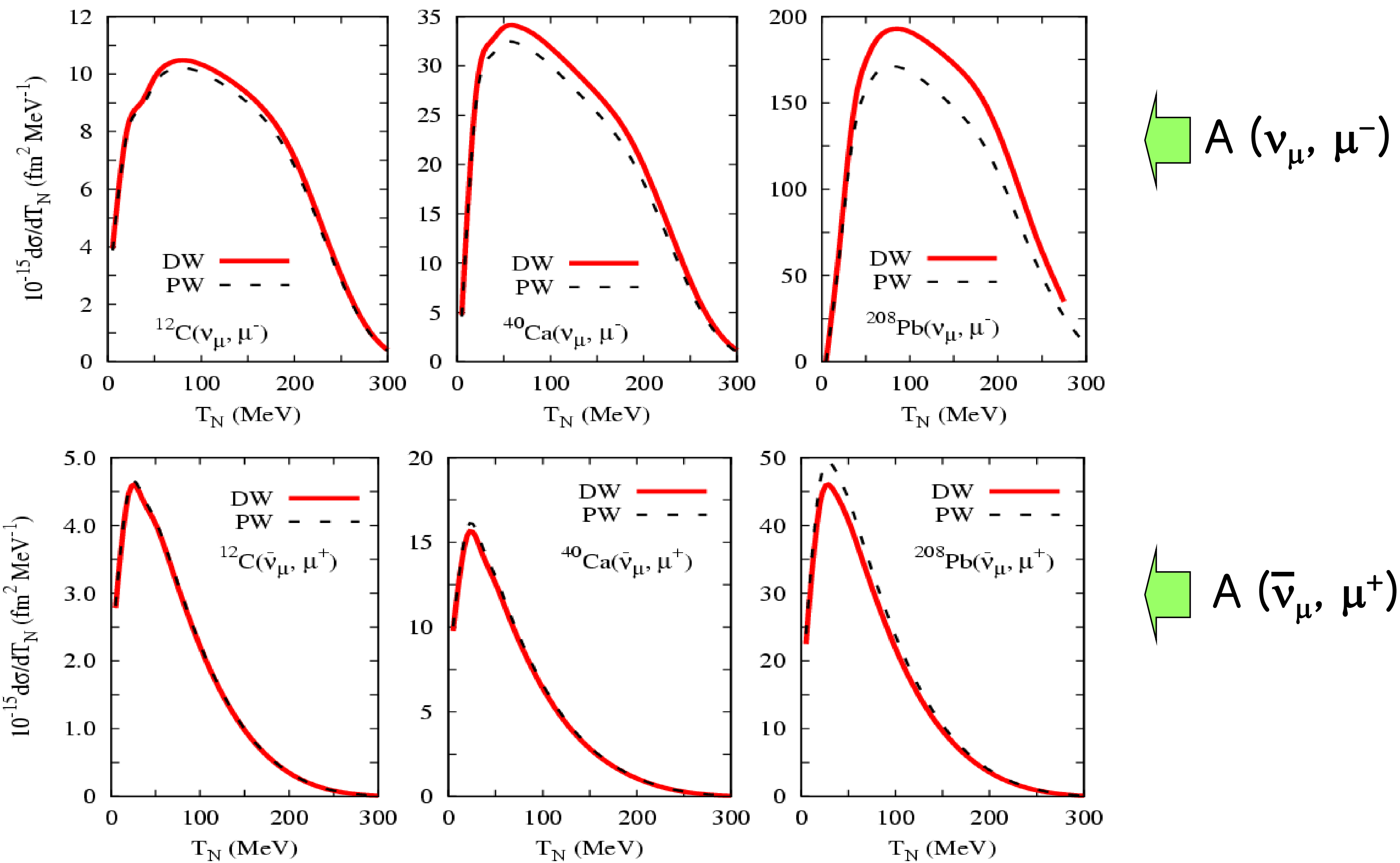
$$\delta(\boldsymbol{\kappa}) = \left[a_0 + a_2 \frac{\boldsymbol{\kappa}^2}{(pR)^2} \right] e^{-1.4\kappa^2/(pR)^2} - \frac{\alpha Z}{2}\left(1 - e^{-\kappa^2/(pR)^2}\right)\ln(1+\boldsymbol{\kappa}^2)$$



charged current neutrino–nucleus scattering

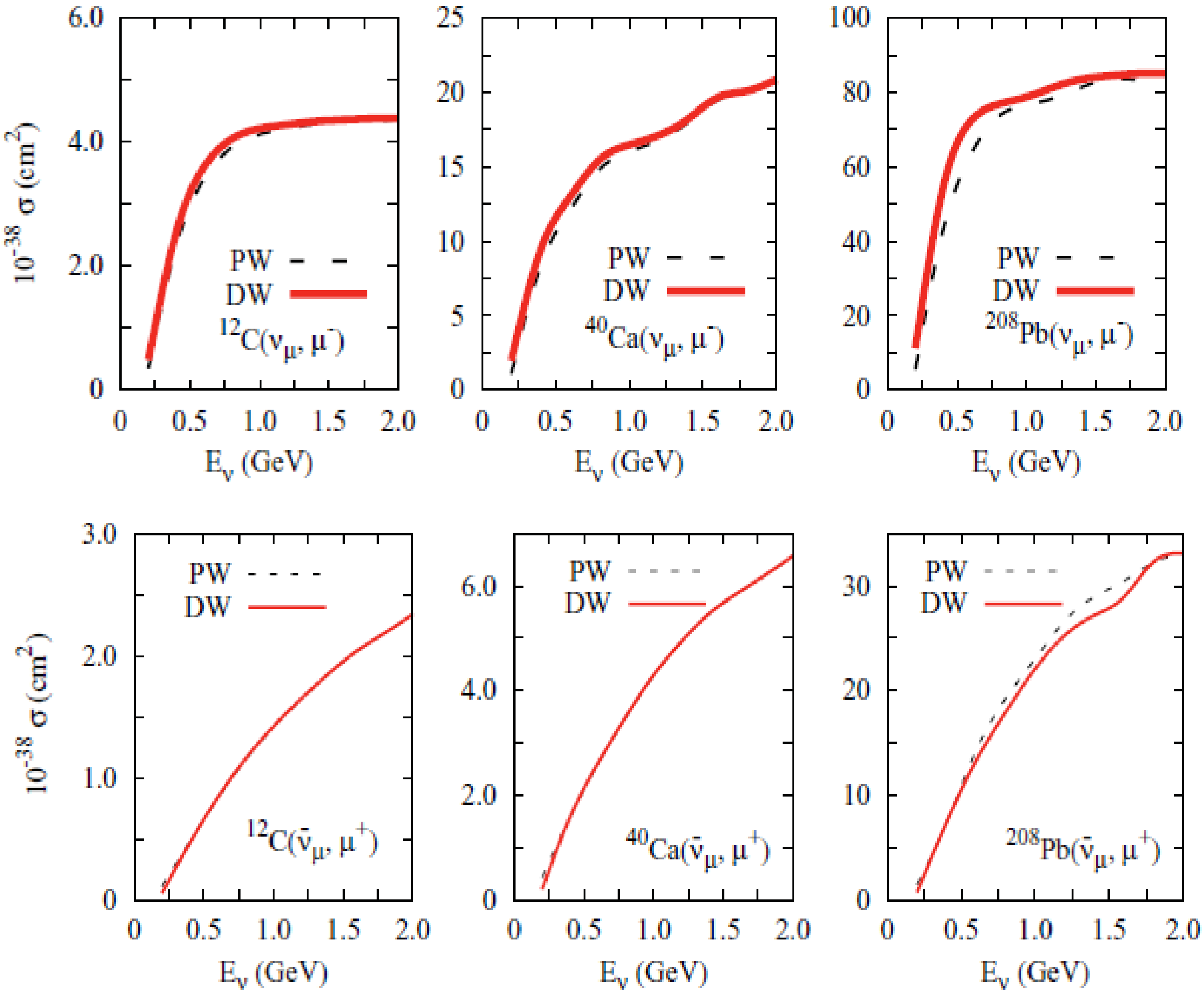
incoming neutrino (antineutrino) energy 500 MeV including the FSI

Ref : PRC 83, 034607 (2011)



Coulomb effect for total cross section

Ref : PRC 83, 034607 (2011)



A (ν_μ, μ^-)

A $(\bar{\nu}_\mu, \mu^+)$

Summary

- The optical potential produces a large reduction (about 50%) of the cross section but the RMF reduces the cross section about 20 %.
- The resultant FSI effects on the contribution to the knocked-out protons are larger than those of the neutrons by 10% for the incident neutrino and 1%～3% for the antineutrino.
- The effect of the density-dependence on g_A is biggest and that on F_1 is very small.
- The effect of density-dependence reduces the cross sections and we compare this data with the experimental data.
- For both proton and neutron, the effect of M_A increases the cross sections but reduces the asymmetry.

- For the case of proton, the effect of g_A^s reduces the cross sections but increases the asymmetry, and for the neutron vice versa. Hence the effect of g_A^s totally reduces the cross sections but increases the asymmetry.

- The effect of μ_s reduces the cross section for incident neutrino and for antineutrino vice versa.

- For the ratios of the NC to CC reactions, one can distinctly study the effect of M_A for the knocked-out proton of the NC reaction.

- Our results describe the NC MiniBooNE experimental data relatively well but do not the CC data.

- The effect of the Coulomb distortion is also one of the important elements. The effects on the total cross section are a few percent for the neutrino and the antineutrino.

Thank you very much