ニュートリノ-原子核散乱の理論の現状と展望

Toru Sato

RCNP,Osaka University

- Introduction
- Quasi-Elastic scattering
- Meson production in resonance region
- Summary

Neutrino nucleon/nucleus reactions

- Hadron/nuclear physics: Unique probe for axial vector structure of nucleon/nuclei
- Neutrino Physics: neutrino flux via neutrino-nucleus reactions
- Astrophysics: neutrino reaction, beta-decay and electron capture in Supernova/neutron star

In current and future long base line neutrino experiments, atmospheric neutrino observation, neutrio properties are extracted from events of neutrino-nucleus reactions.

$$< \sigma_{\nu A} >= \int dE_\nu \sigma_{\nu A}(E_\nu)\phi_\nu(E_\nu)$$

precise understanding of neutrino nucleus reaction in the wide energy range is important to reconstruct neutrino energy, flux then neutrino properties.

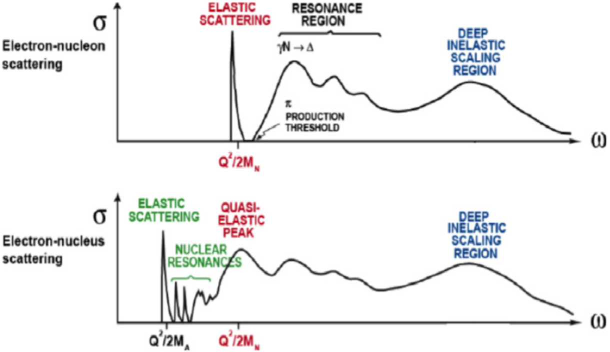
neutrino flux of Long base line accelerator experiments

from a few hundred MeV to a few GeV and wide-band

T2K	$E_\nu \sim$	$0.6 \pm 0.2 (GeV)$
MiniBooNE		0.6 ± 0.6
MINOS/MINERvA(LE)		3.2 ± 1
NOvA		2 ± 0.5
Dune		2 ± 2

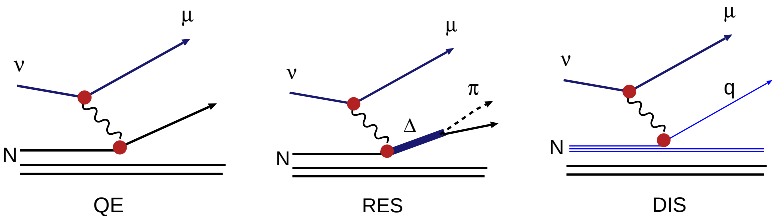
Note: KDAR $E_{\nu_\mu} = 236 MeV$ PRL120 (2018)141802
$\sigma = (2.7 \pm 1.2) \times 10^{-39} cm^2/neutron$

Reaction mechansims of lepton-nucleus reactions



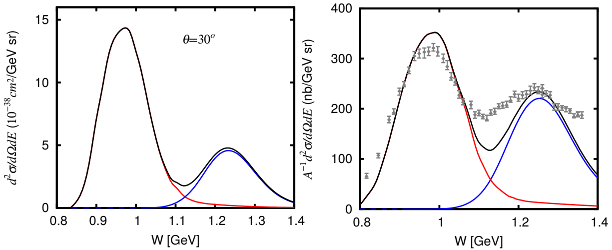
G. T. Garvey et al. Phys. Rep. 580(2015)1

electron-nucleus reaction ω = energy transfer to nucleon/nucleus



QE region

- Neutrino energy is estimated from muon momentum assuming two-body kinematic of $\nu +' n'(at \quad rest) \to \mu^- + p$
- Naively QE ('high energy and momentum transfer' process compared with inelastic excitation of nuclear excited states) can be described simply by initial energy and momentum distribution of nucleon inside nuclei.



B. Szczerbinska et al. PLB649(2007)132

- because of wide band neutrino flux, difficult to extract 'QE' without knowing reaction in non-QE region. $\to$ RPA + 2p2h (Nieves,)
- final state interaction can be important depending on $\vec{q}, \omega$.
- possible non-negligible contribution of two-body nuclear current.

Neutrino-nucleon/nucleus interaction

$$< F\mu^-|H_I|I\nu_\mu >= \frac{G_F V_{ud}}{\sqrt{2}} < \mu^-|\bar{\psi}_\mu\gamma^\lambda(1-\gamma_5)\psi_\nu|\nu_\mu >< F|J_\lambda^{CC}(\vec{q},\omega)|I > \delta(E_I+\omega-E_F)$$

- Elastic scattering:
  $< I|J_\lambda^{CC}|I >$ well known form factor of ground state

  COHERENT science 357(2017)1123 $\rightarrow$ non-standard neutrino int.
  Coherent pion production $CC\pi^+, NC\pi^0$
- Inclusive cross section: sum all nuclear final states $\rightarrow$ $(e,e'X),(\nu,\mu X)$ in QE region

$$R_{\mu\nu}(q) = \sum_F < F|J^\mu_{CC}(q)|I >< FJ^\nu_{CC}(q)|I >^* \delta(E_I+\omega-E_F)$$

$$= -Im[\frac{1}{\pi} < I|(J^\nu_{CC}(q))^\dagger \frac{1}{E_I+\omega-H+i\epsilon} J^\mu_{CC}(q)|I >]$$

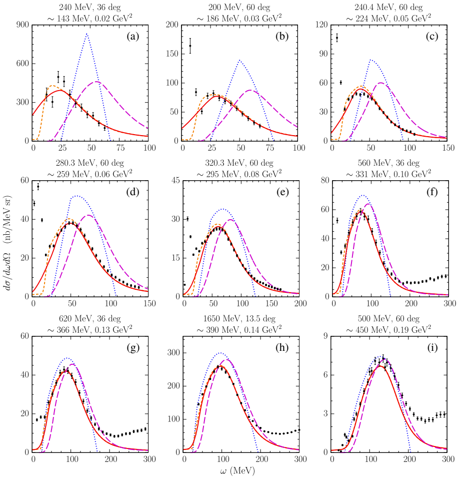
ab initio approach: GFMC, correlated Gaussian +complex scaling(few-nucleon-system)

Nuclear current

- Nucleon current $< p|V^\mu - A^\mu|n >$
  Axial vector form factor: B. Bhattachraya et al. PRD84(2011)073006, 'z-expansion'.
  LQCD: R. Gupta et al. PRD96 (2017),114503, C. Alexandrou et al. PRD96(2017)054507
- Meson exchange current
  meson exchange model(S. Nakamura et al. PRC63 (2001)034617), Chiral EFT

Spectral function and final state interaction

$$P(\vec{k}, E) = \sum_n | < n|a_k|0 > |^2 \delta(E - (E_n(A-1) - E_0(A))$$



A. M. Ankowski et al. PRD91 (2015) 033005

GFMC (brief explanation of 'outsider')

Project ground state from trial wave function $|\psi_T>$.

$$|\psi_0> \propto \lim_{\tau\to\infty} e^{-(H-E_0)\tau}|\psi_T>$$

Inclusive response function $R_\gamma(q,\omega)$ from Euclid response function $E_\gamma(q,\tau)$

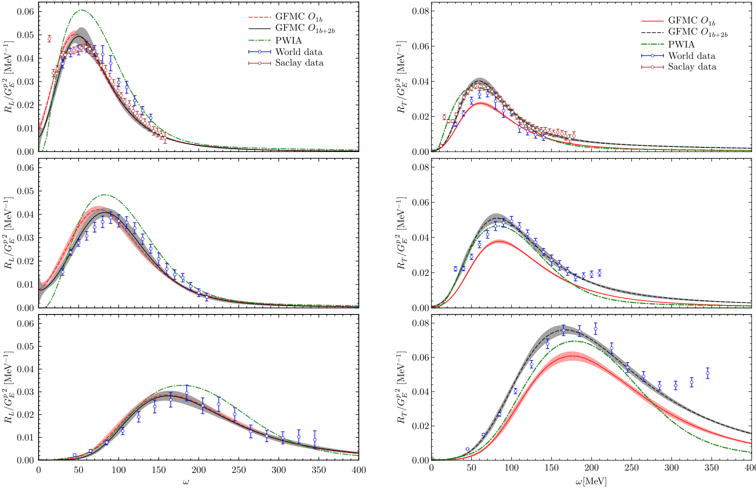
$$E_\gamma(q,\tau) =< \psi_0|O^\dagger_\gamma(q)e^{-(H-E_0)\tau}O_\gamma(q)|\psi_0> -|F_\gamma(q)|^2 e^{-\tau\omega_{el}}$$

Use MEM to invert Laplace transformation

$$E_\gamma(q,\tau) = \int_{\omega_{el}}^{\infty} d\omega e^{-\omega\tau}\frac{R_\gamma(q,\omega)}{(G^p_E(q,\omega))^2}$$

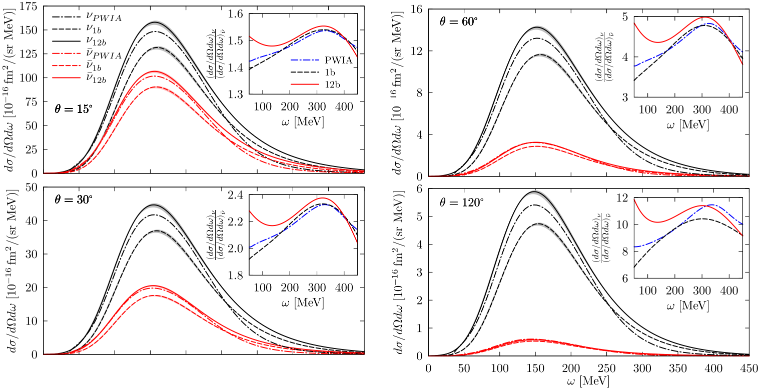
J. Carlson et al. RMP87 (2015)1067,A. Lovato et al. PRL117(2016)082501

$^{12}C(e,e')$ Longitudinal R_L and transverse R_T response functions



A. Lovato et al. PRL 117(2016)082501

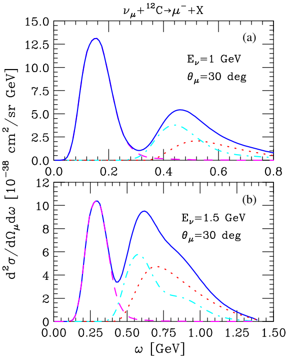
$\nu -^{12} C$ inclusive NC



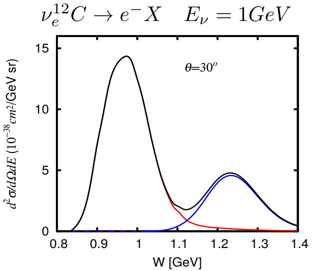
A. Lovato et al., PRC97 (2018)022502

Fix $q = 570MeV$, (at $\theta = 15^o$, $1.6GeV < E_\nu < 2.2GeV$)

Neutrino reaction in resonance region



E. Vagnoni et al. PRL118(2017)142502



B. Szczerbinska et al. PLB649 (2007)132

QE + Res + DIS

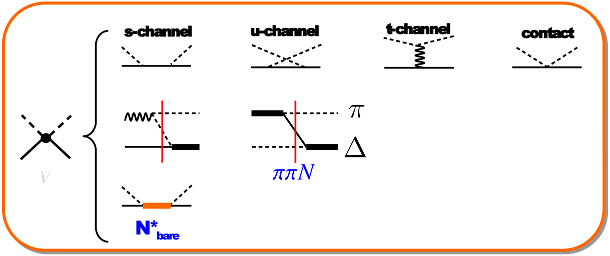
QE + Delta

CC Neutrino-nucleon reaction (building block to describe neutrino-nucleus reaction)

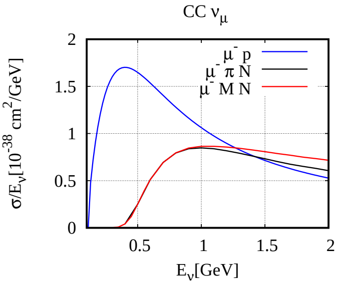
$$
\begin{aligned}
\nu + N \quad \rightarrow \quad & l + N \\
& l + N + \pi \\
& l + N + \eta \\
& l + Y + K \\
& l + N + \pi + \pi \\
& .... \\
& l + Y \\
& l + N + K \\
& ....
\end{aligned}
$$

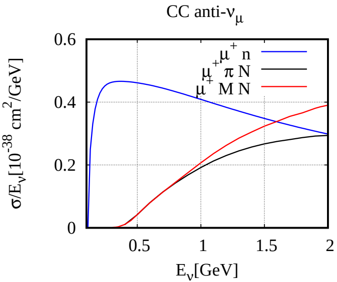
Dynamical Coupled Channel model (ANL-Osaka DCC model):

- include N^*, Δ resonances
- coupled channel model $\pi N, \eta N, \pi\pi N(\sigma N, \rho N, \pi\Delta), K\Lambda, K\Sigma$
- Satisfy three body($\pi\pi N$) unitarity



Neutrino-nucleon cross section





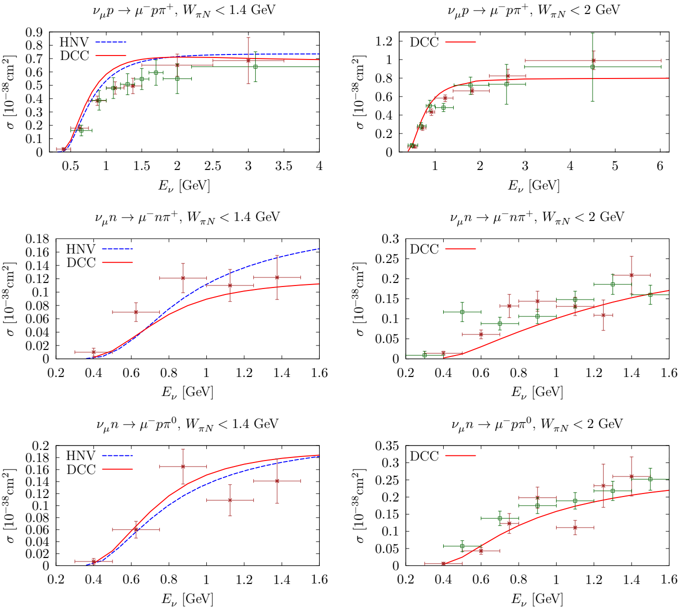
- cross section of single pion production is as large as non-meson production (DCC model, S. X. Nakamura et al.)
- non negligible contribution of $2\pi, K, \eta$ production channels($\bar{\nu}$).

Model of single pion production around Δ_{33}

comparison of models I : total cross section of single pion production

J. E. Sobczyk, E. Hernandez, S. X. Nakamura, J. Nieves, T. Sato, arXiv:1807.11281

- DCC: ANL-Osaka
- HNV: E. Hernandez, J. Nieves, M. Valverde
  - single pion production in Δ region
  - non-resonant interaction from chiral Lagrangian
  - Unitarity (Satisfy Watson theorem for P_{33})



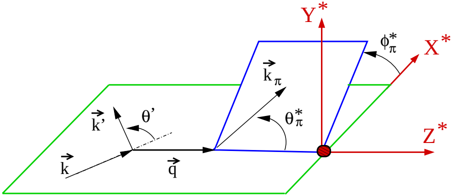
DCC $0.9 g_{AN\Delta}$

comparison of models II : Angular distribution of pion production off nucleons

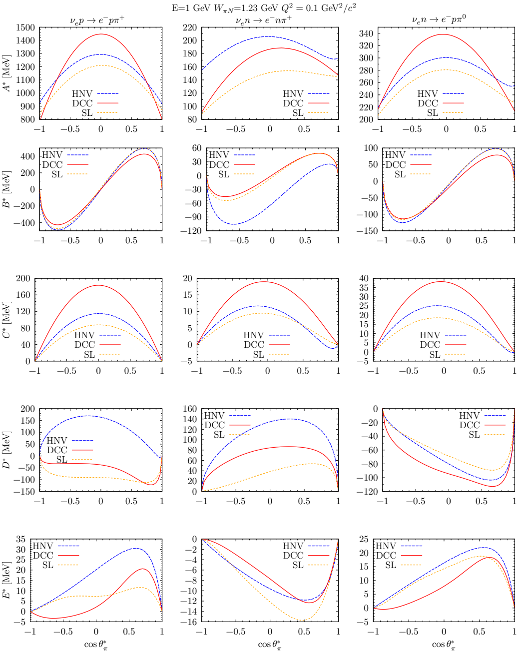
$$\frac{d\sigma^{CC}}{dW_{\pi N} dQ^2 d\Omega^*_\pi} = \frac{G_F^2 W_{\pi N}}{4\pi M k^2}[A + B\cos\phi_\pi + C\cos 2\phi_\pi + D\sin\phi_\pi + E\sin 2\phi_\pi]$$

T.Sato, D. Uno, T. -S. H. Lee (2003), E. Hernandez, J.Nieves, M. Valverde, PRD76, 033005 (2007)

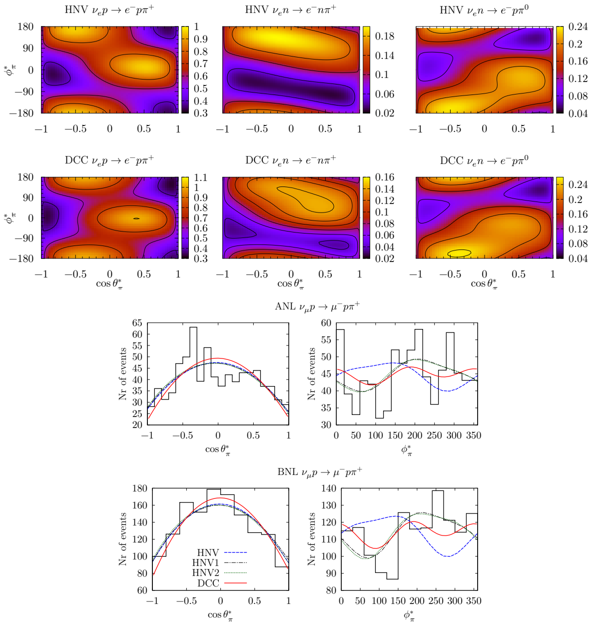
- parity violating T-odd angular distributions are generated.
- angular distribution pion may reveal differences among models that are not seen well in integrated cross sections.



PV: $\sin\phi_\pi \sim \boldsymbol{k} \times \boldsymbol{k}' \cdot \boldsymbol{k}_\pi$



E=1 GeV $W_{\pi N}$=1.23 GeV $Q^2 = 0.1$ GeV$^2/c^2$
$\nu_e p \to e^- p \pi^+$
$\nu_e n \to e^- n \pi^+$
$\nu_e n \to e^- p \pi^0$
A^* [MeV]
B^* [MeV]
C^* [MeV]
D^* [MeV]
E^* [MeV]
HNV
DCC
SL
$\cos\theta^*_\pi$


HNV $\nu_e p \to e^- p \pi^+$
HNV $\nu_e n \to e^- n \pi^+$
HNV $\nu_e n \to e^- p \pi^0$
DCC $\nu_e p \to e^- p \pi^+$
DCC $\nu_e n \to e^- n \pi^+$
DCC $\nu_e n \to e^- p \pi^0$
ϕ^*_π
$\cos\theta^*_\pi$
ANL $\nu_\mu p \to \mu^- p \pi^+$
BNL $\nu_\mu p \to \mu^- p \pi^+$
Nr of events
HNV
HNV1
HNV2
DCC

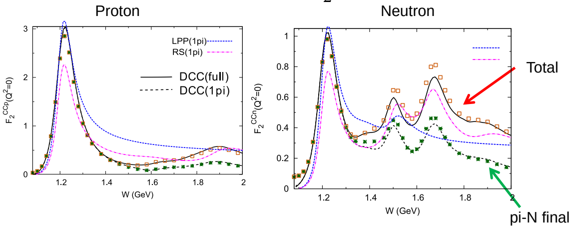
Neutrino-nucleon reaction beyond Δ resonance

How well DCC model accounts inclusive strength ?

- $Q^2 = 0$ PCAC (compare with πN total and elastic cross sections)
- Large Q^2
  vector current : data and parton model
  axial vector current : parton model, PV electron scattering

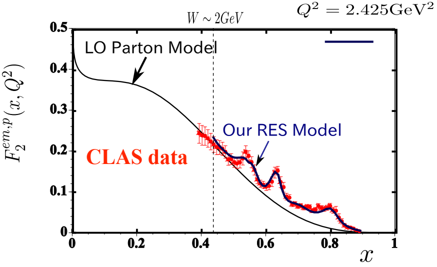
$Q^2 = 0$ PCAC (compare with πN)

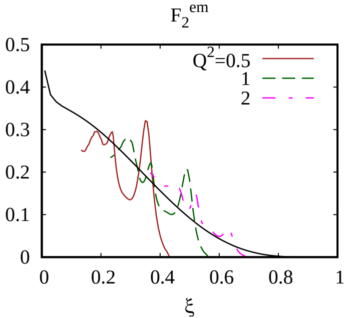
Axial Vector current F_2^{CC} at $Q^2 = 0$



Using PCAC, $F_2^{CC}(Q^2 = 0) = \frac{2f_\pi^2}{\pi}\sigma(virtual\pi + N)$

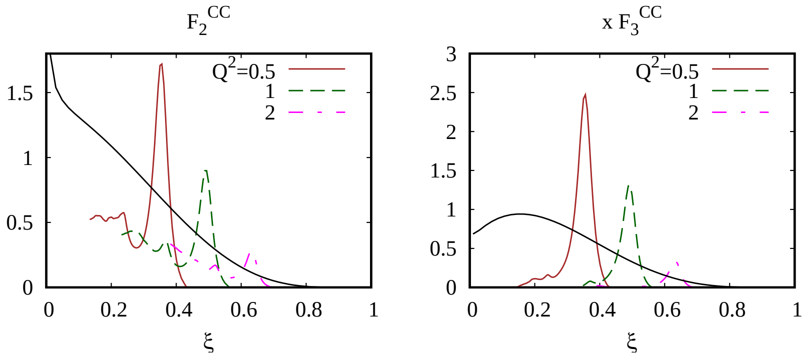
Large Q^2 Vector current





$$F_i^\alpha = \frac{F_{ip}^\alpha + F_{in}^\alpha}{2}$$

Large Q^2 Axial vector current



$F_2^{CC} \sim |V|^2 + |A|^2, F_3^{CC} \sim Re(VA^*)$ suggesting strength of axial vector current at large W, Q^2 is too weak.

Approximate relation between structure functions

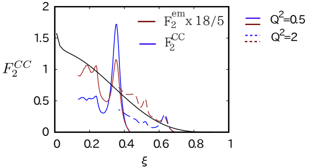
- F_3^{CC} and $F_3^{\gamma Z}$ $(F_i^\alpha = (F_{ip}^\alpha + F_{in}^\alpha)/2)$

$$
\begin{aligned}
2F_3^{\gamma Z} &= F_3^{CC} \propto V_{IV}(A_{IV})^* && \text{DCC} \\
2F_3^{\gamma Z} &\approx F_3^{CC} \sim u - \bar{u} + d - \bar{d} && \text{PDF}
\end{aligned}
$$

* $W_3^{\gamma N}$ can be used to test F_3^{CC} for neutrino reaction.

- F_2^{CC} and F_2^{em}

$$
\begin{aligned}
F_2^{CC} &\propto |V_{IV}|^2 + |A_{IV}|^2, \quad F_2^{em} \propto |V_{em}|^2 && \text{DCC} \\
F_2^{CC} &\approx \frac{18}{5} F_2^{em} \sim x(u + \bar{u} + d + \bar{d}) && \text{PDF}
\end{aligned}
$$



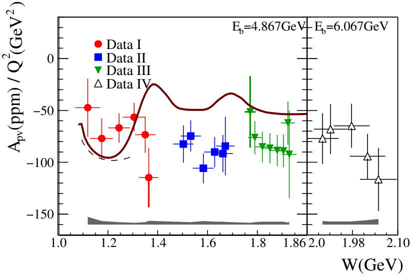
Parity Violating Asymmetries

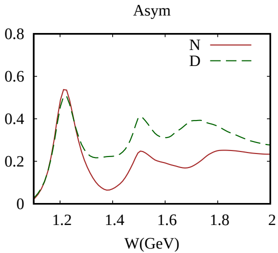
Parity violating asymmetry of $d(\vec{e}, e')$ reaction

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{Q^2 G_F}{\sqrt{2}4\pi\alpha}\frac{N}{D}$$

$$N = \cos^2\frac{\theta}{2}W_2^{\gamma Z} + \sin^2\frac{\theta}{2}[2W_1^{\gamma Z} + (1 - 4\sin^2\theta_W)\frac{E_e + E_e'}{M_N}W_3^{\gamma Z}]$$

$$D = \cos^2\frac{\theta}{2}W_2^{em} + \sin^2\frac{\theta}{2}W_1^{em}$$





The PVDIS Collaboration PRC91 045506 (2015) ($E_e = 4.867GeV, \theta = 12.9^o$)

summary

- Neutrino-nucleus reaction in QE region
  - Brief review of theoretical approaches to describe QE region
  - ab initio nuclear many body calculation revleals importance of FSI and MEC in QE region. MEC of axial vector current at higher Q^2 is not well tested.
- Neutrino induced meson production
  - Comparison of theoretical models for angular distribution of single pion production was discussed. Findings of microscopic calculation should be implemented in generators of neutrino reaction.
  - Further analysis of Axial vector current in nucleon resonance region at moderate and high Q^2 region is important for neutrino and hadron physics.