theory of pion production for nu-d - Neutrino induced pion production reaction on deuteron -

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νd, γd: S.X. Nakamura, H. Kamano, T. -S. H. Lee
pion angular distribution: J. E. Sobczyk, E. Hernandez, S. X. Nakamura, J. Nieves

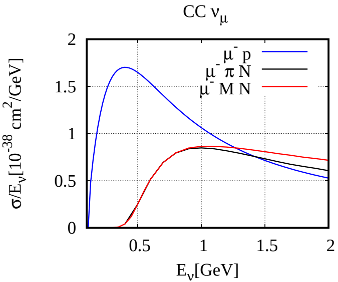
- Motivation
- Models of neutrino induced pion production reactions
- Neutrino deuteron reaction and extraction of elementary cross section
- Summary

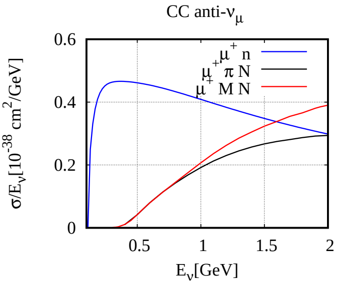
Motivation

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

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

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($\bar{\nu}$).

Single pion production

$$\nu_\mu + p \to \mu^- + \pi^+ + p, \quad \bar{\nu}_\mu + n \to \mu^+ + \pi^- + n$$
$$\nu_\mu + n \to \mu^- + \pi^+ + n, \quad \bar{\nu}_\mu + p \to \mu^+ + \pi^- + p$$
$$\nu_\mu + n \to \mu^- + \pi^0 + p, \quad \bar{\nu}_\mu + p \to \mu^+ + \pi^0 + n$$

Cross sections

$$\sigma(E_\nu), \quad \frac{d\sigma}{dQ^2}, \quad \frac{d\sigma}{dW_{\pi N}}, \quad \frac{d\sigma}{dW_{\pi N} dQ^2 d\Omega_\pi}$$

Data on single pion production

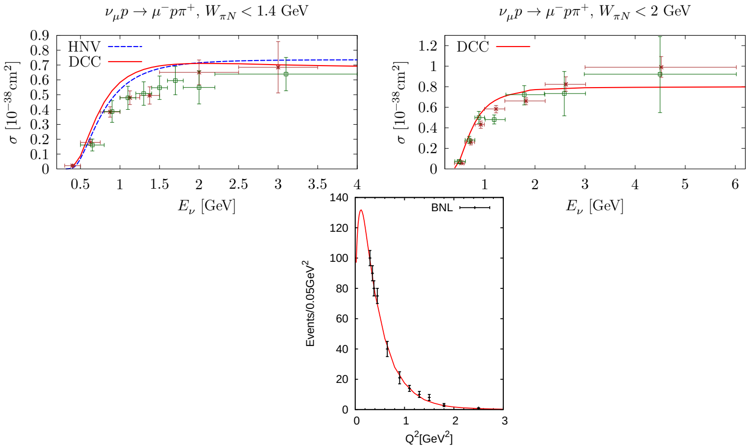
Data on Neutrino induced Single pion production

(http://hepdata.cedar.ac.uk/review/neutrino/)

				1π	2π
GGM	Lerche 1978	ν	Propane	1-10	
	Bolognese 1979	$\bar{\nu}$	Propane-Freon	1-7.5	
BEBC	Allen 1986	ν	p	10-80	
	Allasia 1990	$\nu, \bar{\nu}$	d	5-150	
BNL	Kitagaki 1986	ν	d	0.5 - 3	0.5 - 3
ANL	Barish 1979	ν	p,d	0.4 - 6	
	Radecky 1982	ν	d	0.5 - 1.5	
	Day 1983	ν	d		0.75-5.55
FNAL	Bell 1978	ν	p	15-40	
SKAT	Ammosov 1988	ν	Freon(CF_3Br)	4-18	
	Grabosch 1989	$\nu, \bar{\nu}$	Freon(CF_3Br)	3.5-6	

- Reanalysis of ANL/BNL data
  (C. Wilkinson et al. PRD90 (2014), P. Rodrigues, C. Wilkinson, K. McFarland, EPJC76 (2016))

models of pion production are 'tested' against ANL/BNL data.



$\sigma(\nu N)_{exp}$ are extracted from νd data without taking into account FSI.

$$< F|j^\mu_{CC}|I > \sim < (\pi NN)_{PLW}|j^\mu_{CC}|d >$$

- It is well known FSI is important for $\gamma d \to \pi^0 pn$ and not so important for $\gamma d \to \pi^- pp$. (channel dependent role of FSI)
- more than 30% effects of FSI on pion angular distribution $\frac{d\sigma}{dE_\mu d\Omega_\mu d\Omega_\pi}$ around 'QE' Δ production kinematics have been pointed out. Jia-jun Wu, T. -S. H. Lee, T. Sato PRC91 (2015)

in this talk

- Extend our previous analysis to cover whole phase space of $\mu^- \pi NN$ to examine how important final state interaction in $\nu + d \to l + \pi + N + N$.
Try to extract $\sigma(\nu N)$ from νd data without full microscopic calculation.

Model of meson production

$$\boxed{< MB|J^{\mu}_{\alpha}|N >}$$

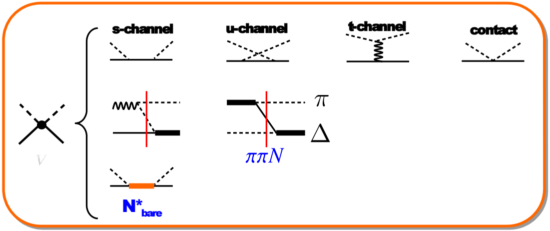
$$
\begin{aligned}
J^{\mu}_{em} &= V^{\mu}_{3} + V^{\mu}_{IS} \\
J^{\mu}_{CC} &= V^{\mu}_{1+i2} - A^{\mu}_{1+i2} \quad (\Delta S = 0 \text{ current without CKM}) \\
J^{\mu}_{NC} &= V^{\mu}_{3} - A^{\mu}_{3} - 2\sin^2\theta_W J^{\mu}_{em} - \frac{1}{2}\bar{s}\gamma^{\mu}(1-\gamma_5)s
\end{aligned}
$$

- meson production through resonance excitation and non-resonant mechanisms.
- model should be constrained as much as possible by existing data on pion, photon and electron induced reactions.

ANL-Osaka DCC model

Model developed for N^* physics: spectrum of $N^*, \Delta(W < 2GeV)$,transition form factors

- Fock-Space:isobar(N^*, Δ) , Meson-Baryon $(\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N))$
- Coupled-channel(Lippmann-Schwinger)equation is solved numerically.

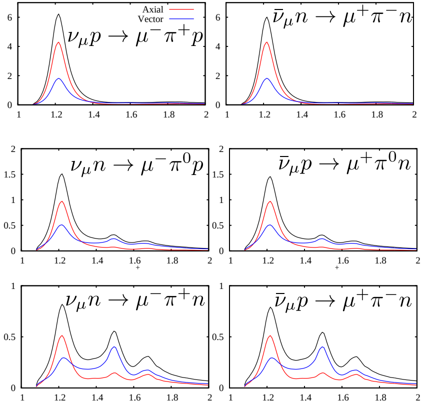


- analyze available data on pion, photon, electron induced meson production

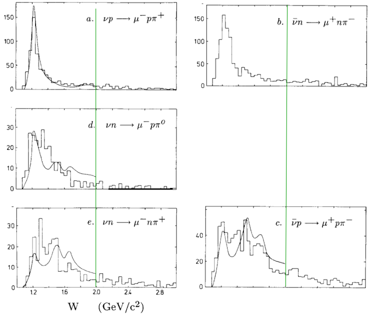
$$
\begin{aligned}
\pi p &\rightarrow \pi N, \eta N, K\Lambda, K\Sigma \\
\gamma p/n &\rightarrow \pi N, \eta N, K\Lambda, K\Sigma \\
ep &\rightarrow e'\pi N
\end{aligned}
$$

- resonance spectrum and coupling constants, form factors at resonance pole are extracted from the analytic continuation of the amplitude.
- neutrino reaction: Axial vector current : $g_A^{NN^*}$ from $g_\pi^{NN^*}$ assuming PCAC and dipole form factor, except $\Delta(1232)$.

$d\sigma/dW_{\pi N}$ of single pion production $E_\nu = 40GeV$



Neutrino anti-neutrino



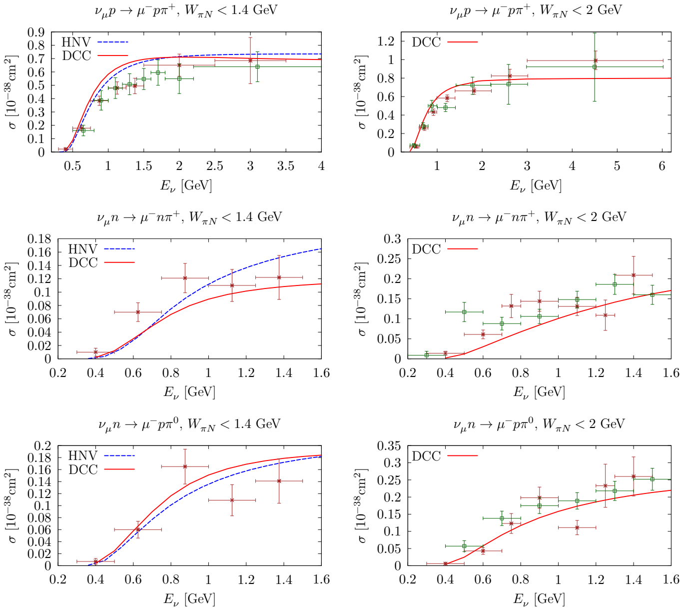
BEBC NP343,285(1990)

- $\Delta(1232)$ gives most important contribution for all channels.
- One can make only qualitative test of model for W dependence.

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

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

- 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})



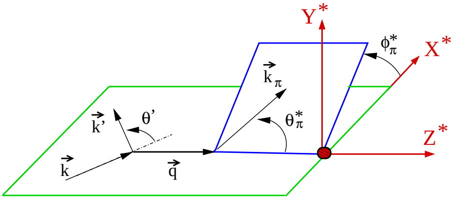
DCC $0.9g_{AN\Delta}$

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

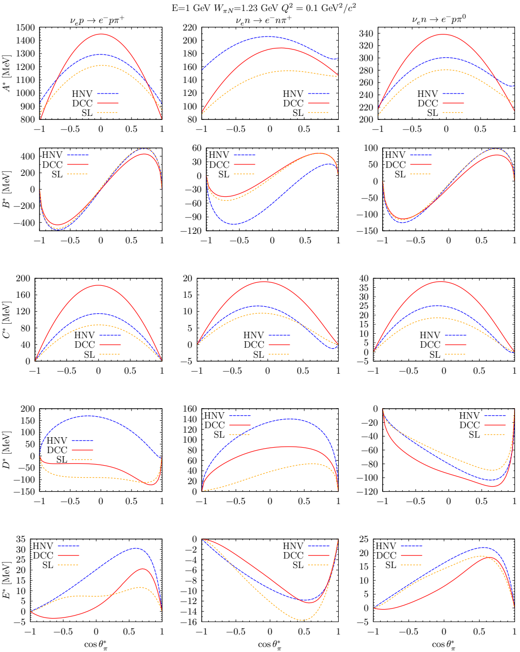
$$\frac{d\sigma^{CC}}{dW_{\pi N} dQ^2 d\Omega^*_\pi} = \frac{G_F^2 W_{\pi N}}{4\pi M k^2}[A + B\cos\phi_\pi + C\cos 2\phi_\pi + D\sin\phi_\pi + E\sin 2\phi_\pi]$$

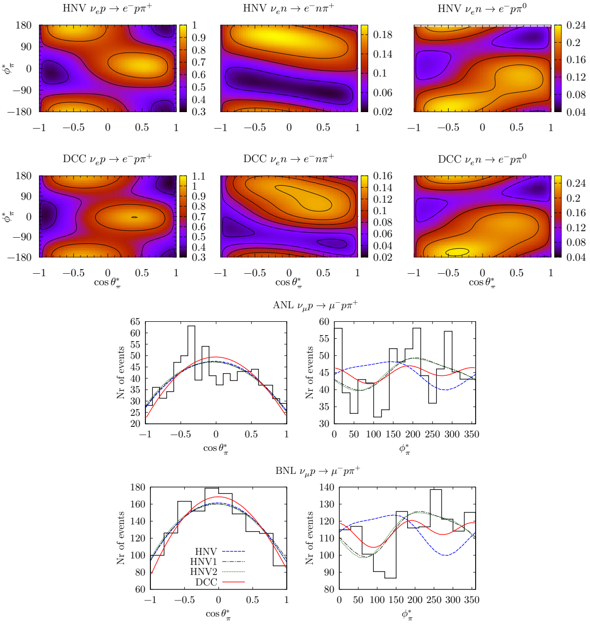
T.Sato, D. Uno, T. -S. H. Lee (2003), E. Hernandez, J.Nieves, M. Valverde, PRD76, 033005 (2007)

- 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
$\cos\theta^*_\pi$

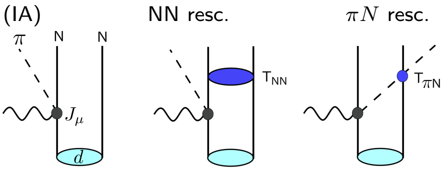

HNV $\nu_e p \to e^- p \pi^+$
HNV $\nu_e n \to e^- n \pi^+$
HNV $\nu_e n \to e^- p \pi^0$
DCC $\nu_e p \to e^- p \pi^+$
DCC $\nu_e n \to e^- n \pi^+$
DCC $\nu_e n \to e^- p \pi^0$
ϕ^*_π
$\cos\theta^*_\pi$
ANL $\nu_\mu p \to \mu^- p \pi^+$
BNL $\nu_\mu p \to \mu^- p \pi^+$
Nr of events
HNV
HNV1
HNV2
DCC

Neutrino induced pion production on deuteron

- how important final state interaction in $\nu + d \to l + \pi + N + N$?
  simple recipe to extract $\sigma(\nu N)$ from νd data?

leading order terms of FSI

$$|[\pi NN]_{PLW} > \rightarrow (1 + G_0 T_{NN} + G_0 T_{\pi N})|[\pi NN]_{PLW} >$$



note:

- Above rescattering terms are the leading order of multiple scattering theory(Faddeev Eq.). More elaborate description of three-body(πNN) dynamics may be possible(A. Matsuyama T.-S.H.Lee PRC34(1986), M. Schwamb Phys. Rep. 485(2010))
- 'Meson exchange current' is not considered.

T. Sato et al.: Electron Scattering and Charged Pion Photoproduction on ^{12}C and ^{13}C 511

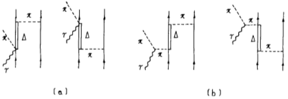


Fig. 4a and b. Two-body operators due to the virtual isobar. Diagrams **a** and **b** are corrections to the Kroll-Ruderman and the pion pole terms, respectively.

TS,K.Koshigiri, H. Ohtsubo,Z.Phys.A320(1985)

Example of NN rescattering amplitude

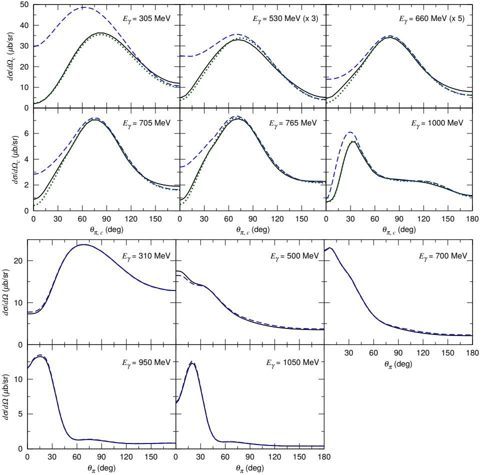
$$
\begin{aligned}
J_\mu^{NN-resc} &= \;<[\pi NN]_{PLW}|t_{NN}G_0 J_\mu^{CC}|d>= \sum_{spin,isospin} \int d\boldsymbol{l} \\
&\times \;\langle N_1(\boldsymbol{p}_1)\, N_2(\boldsymbol{p}_2)|t_{NN}(M_{N_1N_2})|\tilde{N}_1'(\boldsymbol{q}-\boldsymbol{k}+\boldsymbol{l})\, N_2'(-\boldsymbol{l})\rangle \\
&\times \;\frac{\langle \pi(\boldsymbol{k})\, \tilde{N}_1'(\boldsymbol{q}-\boldsymbol{k}+\boldsymbol{l})|J_\mu(W,\boldsymbol{q})|N_1'(\boldsymbol{l})\rangle}{E - E_N(\boldsymbol{q}-\boldsymbol{k}+\boldsymbol{l}) - E_N(-\boldsymbol{l}) - E_\pi(\boldsymbol{k}) + i\epsilon} \langle N_1'(\boldsymbol{l})\, N_2'(-\boldsymbol{l})|\Psi_d(s_d)\rangle
\end{aligned}
$$

- ANL-Osaka model: $J_{CC}^{\mu}, t_{\pi N}$
  Bonn-NN-potential: t_{NN}
- 3dim loop integration + 7-dim phase space(Monte-Carlo)

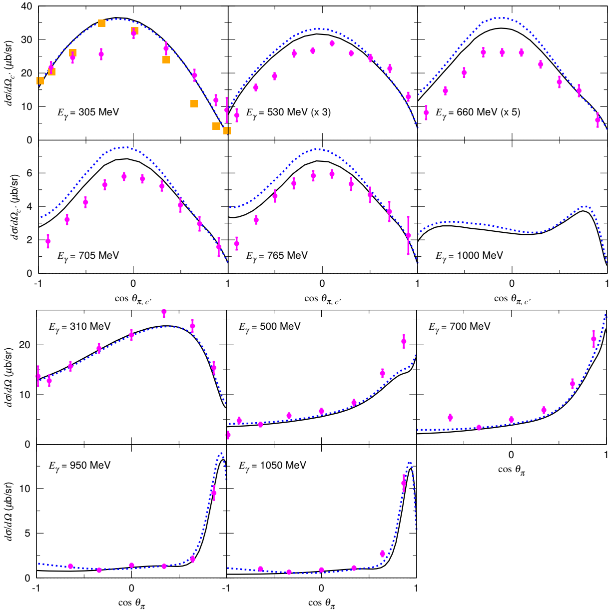
Effects of FSI on $\gamma d \to \pi N N$ S. X. Nakamura et al. arXiv 1804.04757

$\gamma d \to \pi^0 pn$

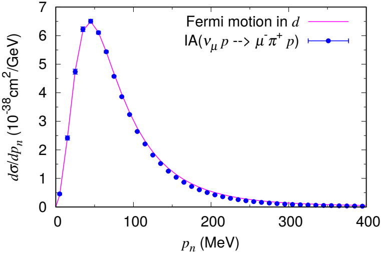
$\gamma d \to \pi^- pp$

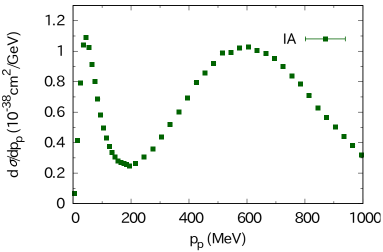


- Large FSI for π^0 production. ${}^3S_1$ scattering state is orthogonal to deuteron bound state. (in DW, deuteron component is eliminated from NN PLW.)


E_γ = 305 MeV
E_γ = 530 MeV (x 3)
E_γ = 660 MeV (x 5)
E_γ = 705 MeV
E_γ = 765 MeV
E_γ = 1000 MeV
$d\sigma/d\Omega_{c'}$ (μb/sr)
$\cos\theta_{\pi,c'}$
E_γ = 310 MeV
E_γ = 500 MeV
E_γ = 700 MeV
E_γ = 950 MeV
E_γ = 1050 MeV
$d\sigma/d\Omega$ (μb/sr)
$\cos\theta_\pi$

momentum distribution of spectator nucleon $(\nu + d \to \mu^- + \pi^+ + p + n)$
– separate proton and neutron π^+ production reaction —





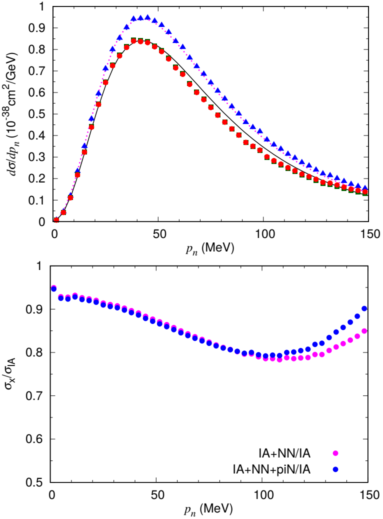
neutron spectator$(p \to \pi^+ p)$

proton spectator$(n \to \pi^+ n)$

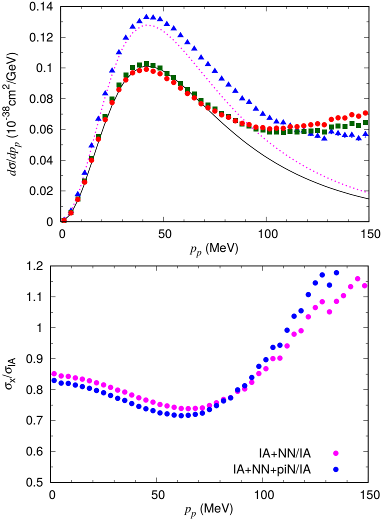
- $p \to \pi^+ p$ $(n \to \pi^+ n)$ mechanism is dominated in $p_n < 150 MeV$ $(p_p < 150 MeV)$.
- (momentum of muon and pion are integrated)

Effects of FSI $\nu_\mu + d \to \mu^- + \pi^+ + p + n \ (E_\nu = 0.5GeV)$

neutron spectator



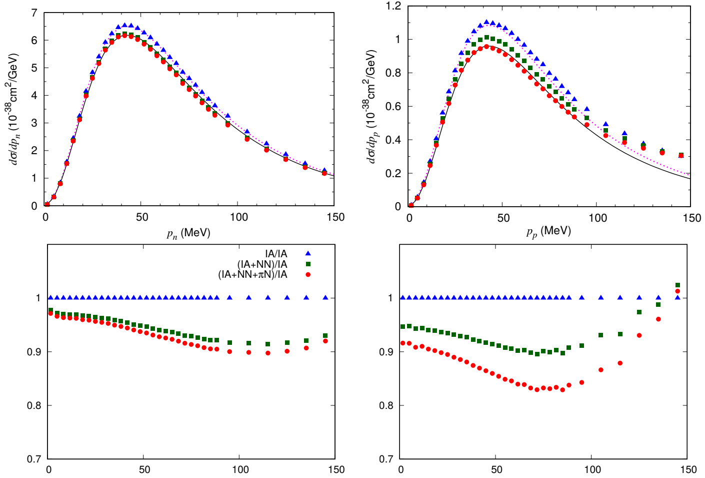
proton spectator



Effects of FSI $\nu_\mu + d \to \mu^- + \pi^+ + p + n$ $(E_\nu = 1GeV)$

neutron spectator

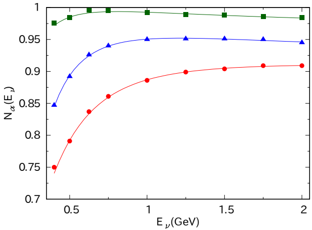
proton spectator



- about $(5 \sim 30)$ % FSI effects depending on E_ν, p_s and channel.

$N_\alpha(E_\nu)$ parametrization of FSI

$$\frac{d\sigma_{\nu d}(E_\nu)}{dp_s} \sim N_\alpha(E_\nu)\frac{d\sigma_{\nu N}}{dp_s}$$
$$\frac{d\sigma_{\nu N}}{dp_s} = p_s^2 \int d\Omega_{p_s}\sigma_\alpha(\tilde{E}_\nu)|\psi_d(\vec{p}_s)|^2$$



$\nu_\mu + n \to \mu^- + \pi^0 + p$

$\nu_\mu + p \to \mu^- + \pi^+ + p$

$\nu_\mu + n \to \mu^- + \pi^+ + n$

- Ideally, one fit data using amplitude with FSI calculated by 'model of elementary amplitude'.
- N_α : fitting 'our' spectator distribution with FSI for $p_s < 50MeV$ by using 'our' 'convoluted' cross section.

Summary

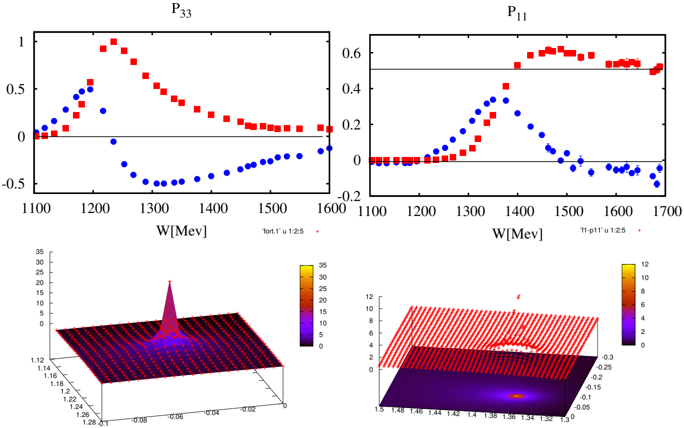
- Pion angular distribution in Δ region is discussed in ANL-Osaka model and HNV model.
  - angular distribution is sensitive to interference among partial wave amplitudes, phase of amplitudes, non-resonant mechanism.
  - parity violating T-odd correlation shows up with non-negligible strength.
- Role of FSI is examined within the first order rescattering correction.
  - pion photoproduction on deuteron is reasonably well described in DCC model+FSI.
  - FSI for the spectator momentum distribution of νd: FSI can be as large as 30% effect depending on E_ν, p_s, channel.
  - Main mechanism of FSI: NN rescattering($p\pi^+, n\pi^+$) πN rescattering ($n\pi^+$) FSI is small for π^0 production.

Acknowledgments KAKENHI JP25105010,JP16K053454.

Backup

Full amplitude is needed, not res-only

$$\pi N \text{ amplitude} \qquad \mathcal{F} = \frac{S-1}{2i}$$



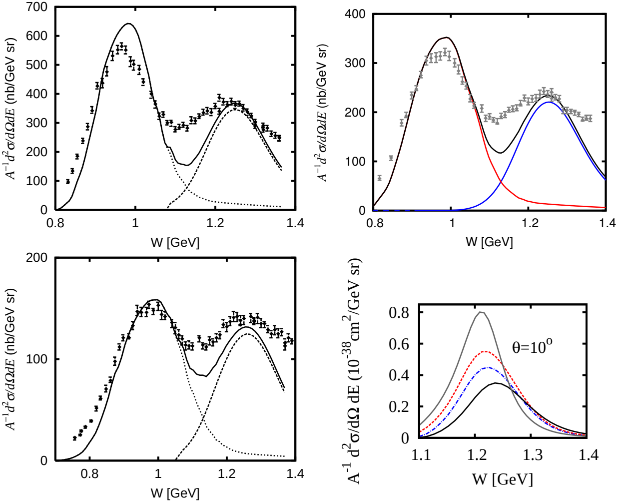
Approximate relation between structure functions

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.

$e^{12}C \rightarrow eX(E_e = 0.96, 1.1, 1.3$ GeV,$\theta_e = 37.5^o)$



B. Szczerbinska, T. Sato, K. Kubodera, T.-S. H. Lee, PLB649(2007) 132

$$L^{\mu\nu}W_{\mu\nu} = \frac{Q^2}{1-\epsilon}\frac{1}{2}\sum_{s'_N,s_N}[R_T + \epsilon R_L + \sqrt{2\epsilon(1+\epsilon)}R_{LT}\cos\phi_\pi + \epsilon R_{TT}\cos 2\phi_\pi$$
$$+\sqrt{2\epsilon(1+\epsilon)}R_{LT'}\sin\phi_\pi + \epsilon R_{TT'}\sin 2\phi_\pi]$$

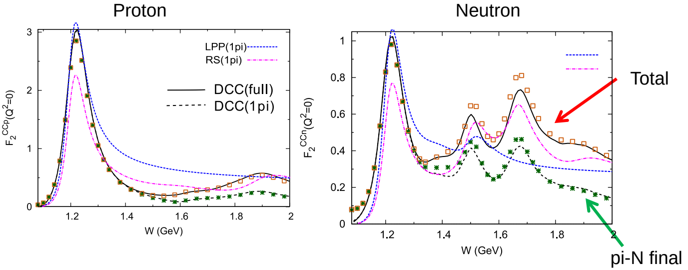
$$R_T = \frac{|j_c^x|^2 + |j_c^y|^2}{2} \mp \sqrt{1-\epsilon^2}\mathrm{Im}(j_c^x j_c^{y*}),$$
$$R_L = \frac{Q^2}{q_c^2}|\bar{j}_c^0|^2,$$
$$R_{LT} = \sqrt{\frac{Q^2}{q_c^2}}[-\mathrm{Re}(\bar{j}_c^0 j_c^{x*}) \pm \sqrt{\frac{1-\epsilon}{1+\epsilon}}\mathrm{Im}(\bar{j}_c^0 j_c^{y*})],$$
$$R_{TT} = \frac{(|j_c^x|^2 - |j_c^y|^2)}{2},$$
$$R_{LT'} = \sqrt{\frac{Q^2}{q_c^2}}[\mathrm{Re}(\bar{j}_c^0 j_c^{y*}) \pm \sqrt{\frac{1-\epsilon}{1+\epsilon}}\mathrm{Im}(\bar{j}_c^0 j_c^{x*})],$$
$$R_{TT'} = -\mathrm{Re}(j_c^x j_c^{y*}),$$

where

$$\epsilon = \frac{1}{1 + \frac{2|\boldsymbol{q}|^2}{Q^2}\tan^2\frac{\theta_l}{2}}$$

Axial vector current at $Q^2 = 0$

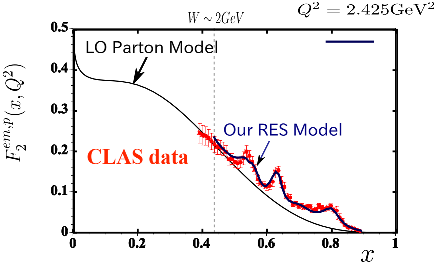
Axial Vector current F_2^{CC} at $Q^2 = 0$

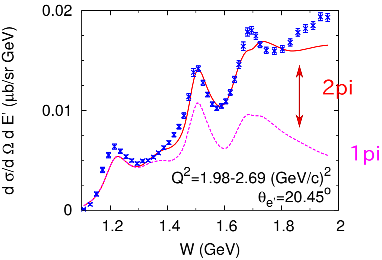


Using PCAC, $F_2^{CC}(Q^2 = 0) = \frac{2f_\pi^2}{\pi}\sigma(virtual\pi + N)$

open box, green cross are data.

Vector current at large Q^2





description of ep in RES, smoothly connected to DIS