Neutrino induced meson production in the resonance region

Toru Sato

RCNP,Osaka University
J-PARC Branch, KEK Theory Center,KEK

- Motivation
- Model of neutrino induced meson production reactions
- Single pion production:W, Q^2, Ω_π distribution. in N^*, Δ resonance region.
- 'inclusive' cross section:F_2^{CC},Adler's sum rule
- Summary

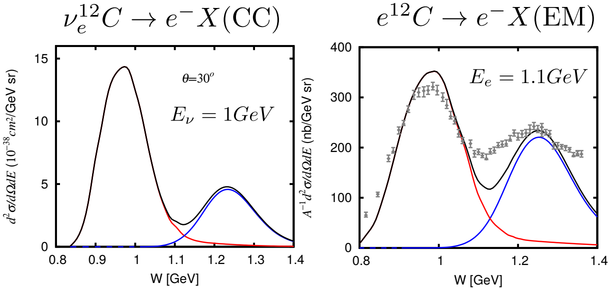
Motivation

- Neutrino Physics:
  In current and future long base line neutrino experiments, atmospheric neutrino observation precise understanding of neutrino nucleus reaction in the wide energy range is important to reconstruct neutrino flux $\phi_\nu(E_\nu)$.

T2K	$E_\nu \sim$	$0.6 \pm 0.2 (GeV)$
Dune		2 ± 2

  (Note: KDAR $E_{\nu_\mu} = 236 MeV$ PRL120 (2018)141802)
- Hadron/nuclear physics: Unique probe of axial vector structure of nucleon/nuclei
  - Axial coupling constants, form factors of N^*, Δ excitation
  - meson production mechanism by axial current

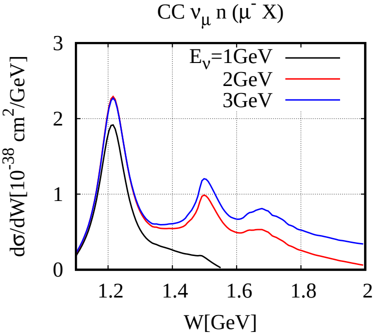
- Pion production and QE



B. Szczerbinska et al. PLB649(2007)132

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

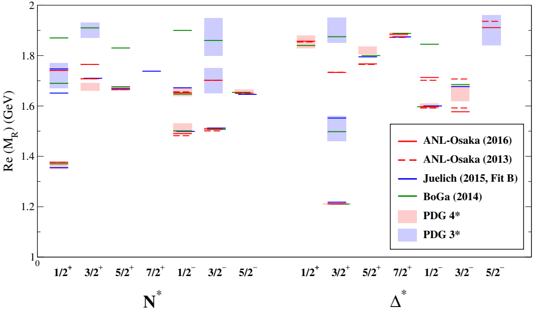
$$
\begin{aligned}
\nu + N \quad \rightarrow \quad & l + N \\
& l + N + \pi \\
& l + N + \eta \\
& l + Y + K \\
& l + N + \pi + \pi \\
& .... \\
& l + Y \\
& l + N + K \\
& ....
\end{aligned}
$$



Neutrino reaction in resonance region

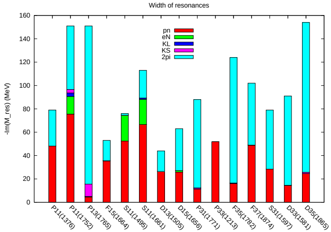
- N^* and Δ resonances

N^*, Δ spectrum (resonance pole of amplitude)



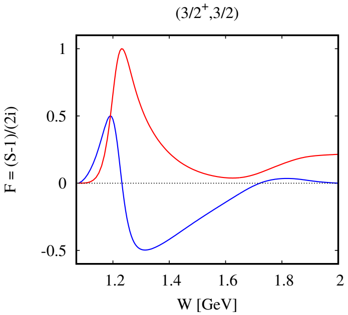
- Opening of meson-baryon channels: $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$..

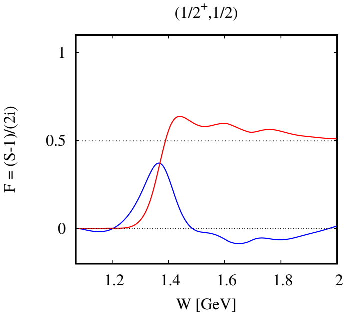
Branching ratio of nucleon resonance (red:πN,blue:$\pi\pi N$)



- Need to describe well resonant/non-resonant mechanism and unitarity

Example: πN amplitude $F = \frac{S-1}{2i} \sim \frac{R}{W - M + i\Gamma/2} + F_{non-res}$



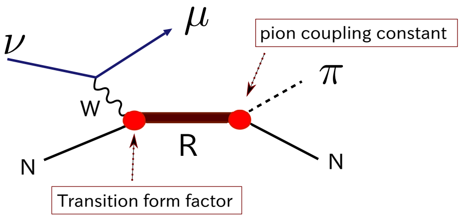


$(Re(F), Im(F))$

$P_{33} : M - i\Gamma/2 = 1211 - i50$

$P_{11} : 1374 - 76i$

Isobar Model



Breit-Wigner formula for partial wave $(J^\pi I)$

$$\frac{g_{\pi NR} \quad g_{JNR}}{W - M_R + i\Gamma_R/2}$$

- Mass(M_R), Width(Γ_R) of resonance R from PDG.
- Coupling constants$g_{\pi NR}, g_{VNR}$ can be estimated from branching ratio(B_α), g_{ANR}: use quark model estimation or use $g_{\pi NR}$ assuming PCAC.

$$g_{\pi NR} = \sqrt{\frac{\Gamma}{2} B_\pi}, \quad g_{VNR} = \sqrt{\frac{\Gamma}{2} B_\gamma}$$

- No control of relative phases between non-res $\leftrightarrow$ res, (J^π, I) channels.

ANL-Osaka DCC model

Model developed for N^* physics: spectrum of nucleon excited states,transition form factors

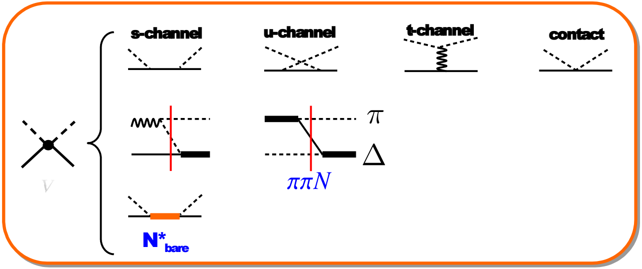
- Fock-Space:isobar(N^*, Δ) , Meson-Baryon ($\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N)$)
- Interaction:isobar excitation and non-resonant meson-baryon interaction
- Coupled-channel(Lippmann-Schwinger)equation is solved numerically.

$$T = V + VG_0T$$

- The model is constructed by fitting available data on pion, photon, electron induced meson production reaction(two-body final state). (Recent model: H. Kamano,S.X. Nakamura L, TS PRC88,035209(2013)
- the model is extended for neutron and axial vector current.
  Neutron: H. Kamano,S.X. Nakamura,T.-S. H. Lee,TS PRC94 015291 (2016)
  Neutrino:S. X. Nakamura,H. Kamano, TS,PRD92 07402(2015)

Brief explanation of Coupled-channel model($\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$)

Physics included inside V



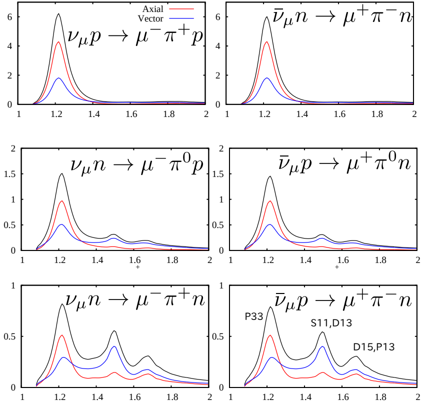
- Differential cross section and polarization data analyzed within the ANL-Osaka Model

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

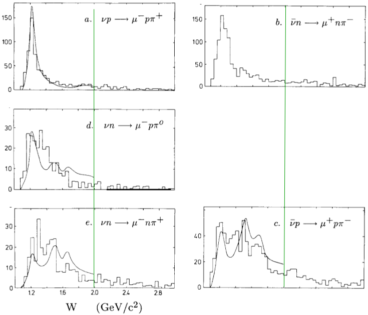
- γn: needed for CC, NC to separate iso-vector from iso-scalar component.
- Axial vector current: $g_A^{NN^*}$ from $g_\pi^{NN^*}$ assuming PCAC and dipole form factor. (Only in Δ region, the model can tested by data.)

Neutrino induced pion production of ANL-Osaka model

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



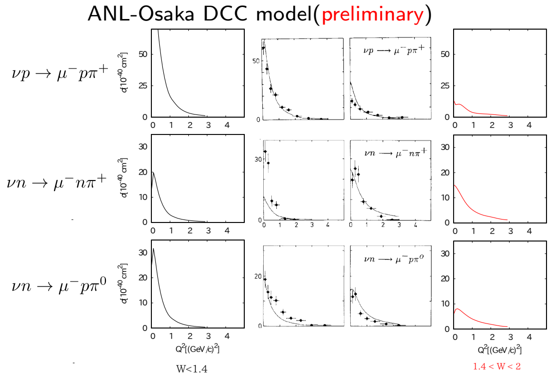
Neutrino anti-neutrino



BEBC NP343,285(1990)

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

Q^2 distibution and strength of higher W



- Reasonable description of single pion production for $W > 1.4GeV$ with DCC model.

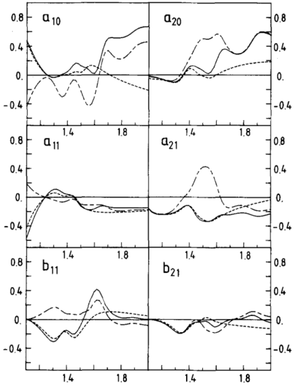
Angular distribution of pion

- Anuglar distribution of pion is sensitive to the interference among partial waves

$$< Y_{lm} > \quad = \quad \frac{\int d\Omega_\pi Y^*_{lm} \frac{d\sigma}{dW d\Omega_\pi}}{\int d\Omega_\pi Y^*_{00} \frac{d\sigma}{dW d\Omega_\pi}}$$

$$a_{lm} = Re(< Y_{lm} >)$$
$$b_{lm} = Im(< Y_{lm} >)$$

W dependence of a_{lm}, b_{lm}

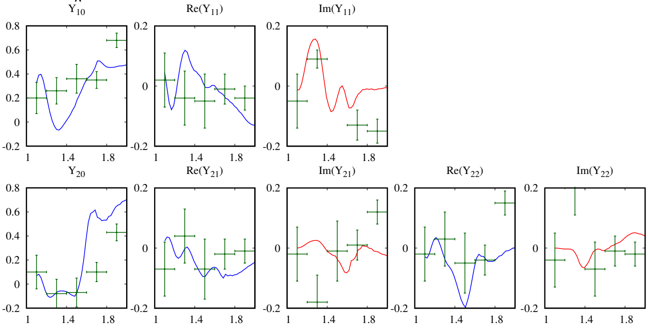


$\bar{\nu} p \to \mu^+ p \pi^-$ Z.Phys.C35,M.Nowakowski

(long dash $\mathcal{M}(S_{11}) \to -\mathcal{M}(S_{11})$)

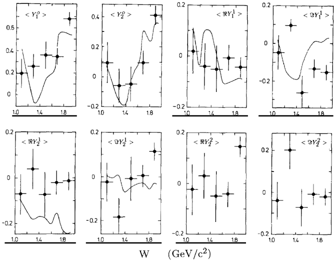
$< Y_{lm} >$ ANL-Osaka Model (preliminary) ($\bar{\nu}p \to \mu^+ p \pi^-$, $E_\nu = 20 GeV$)

$$\frac{d\sigma}{dW d\Omega_\pi} = \sigma_0 + \sigma_c \cos\phi_\pi + \sigma_s \sin\phi_\pi + \sigma_{2c} \cos 2\phi_\pi + \sigma_{2s} \sin 2\phi_\pi$$



Data:NPB343 (1990)D. Allasia et al.

Solid curve: D. Rein Z. Phys.C35



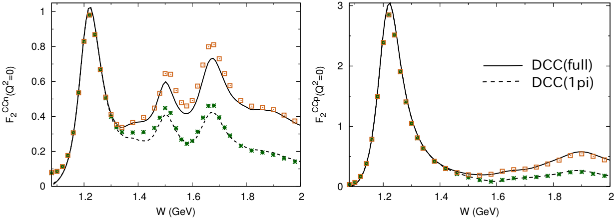
'inclusive' cross section $(\pi N + \pi\pi N + ..)$

Axial Vector current F_2^{CC} (total cross section) at $Q^2 = 0$

DCC model : 1π dash, a Total solid

πN cross section data: 1π green, a Total brown

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

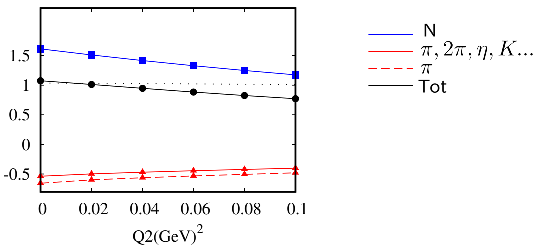


Neutron Proton

- Description of axial vector current at $Q^2 = 0$ is consistent with pion scattering data assuming PCAC.

Adler's sum rule (Axial vector current)preliminary

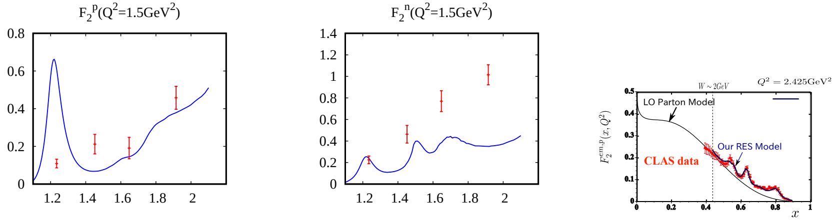
$$1 = [g_A(Q^2)]^2 + \int_{\nu_{th}}^{\infty} [W^A_{2,n}(\nu, Q^2) - W^A_{2,p}(\nu, Q^2)] d\nu$$



- $g_A(Q^2)$: $g_A = 1.27, M_A = 1.1GeV$
- $W^A_{2,n/p}$: DCC model. ν integration: from threshold up to $W = 2GeV$
- $F^{CC}_{2,n} - F^{CC}_{2,p} = 2(F^{CC}_{2,I=1/2} - F^{CC}_{2,I=3/2})/3$

S.L. Adler,PR143(1965)1144,arXiv:0905.2923, E. A. Paschos, D. Schalla, PRD84(2011),013004.

$F^{CC}_{2,p/n}$ and $F^{EM}_{2,p}$



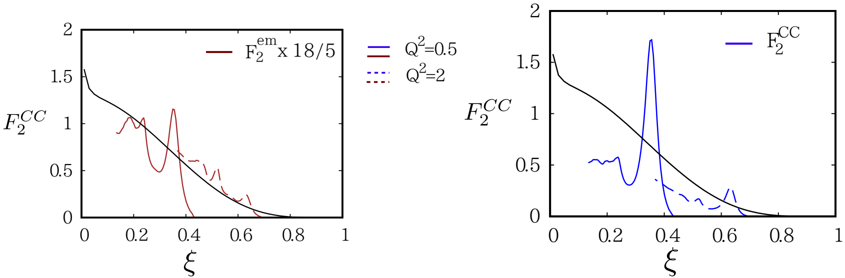
Data: Z. Phys. C28 (1985) Allasia et al.

- $F^{CC}_{2,p} = F^{CC}_{2,I=3/2}$, $F^{CC}_{2,n} = \dfrac{F^{CC}_{2,I=3/2} + 2F^{CC}_{2,I=1/2}}{3}$
- $F_2(V) >> F_2(A)$ at high W, Q^2 in DCC model, while $F^{CC}_2(A) \sim F^{CC}_2(V)$ in parton picture.

High Q^2 region ($F_2^{CC} = \dfrac{F_{2,p}^{CC} + F_{2,n}^{CC}}{2}$)

- (Left) $F_2^{em} \times 18/5$ of ANL-Osaka Model.

$$F_2^{CC} \approx \frac{18}{5} F_2^{em} \sim x(u + \bar{u} + d + \bar{d}) \quad \text{PDF}$$



- (Right)F_2^{CC} of ANL-Osaka Model $\quad F_2^{CC} \propto |V_{IV}|^2 + |A_{IV}|^2 \quad$ DCC

  - Challenging task: model of meson production reaction with $F_2^V \sim F_2^A$ around $W \sim 2GeV, Q^2 \sim 1 - 2GeV^2$ -

Summary

- ANL-OSAKA DCC model is extended to describe weak meson production reaction up to $W < 2GeV$.
- Neutrino induced single pon production in N^*, Δ resonance region is studied using ANL-Osaka model.
  Phase among partial waves/ interplay between non-resonant and resonant mechanism are important for angular distribution of pion.
  Feature of data can be understood within ANL-Osaka model.
  Comparison with Neutrino event generators(NEUT, GENIE,NuWro,..) and other models will be very useful.
- Model of axial vector current is examined.
  At $Q^2 = 0$, DCC model reproduce πN data.
  Adler sum rule might give a hint on description of axial current in resonance region with finite Q^2.
  Comparison with PDF at high Q^2, suggests need for more strength at high W region.
  PV asymmetry , in principle, gives information of axial vector current.

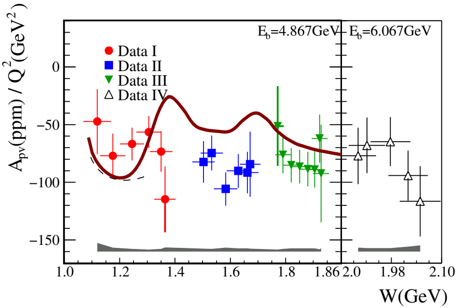
Back up

Possibility to study A_μ^{CC}: Parity violating asymmetry $N(\vec{e},e')X$

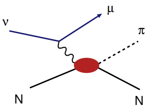
$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

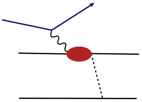
$$= -\frac{Q^2 G_F}{\sqrt{2}4\pi\alpha} \frac{\cos^2\frac{\theta}{2}W_2^{\gamma Z} + \sin^2\frac{\theta}{2}[2W_1^{\gamma Z} + (1-4\sin^2\theta_W)\frac{E_e+E'_e}{M_N}W_3^{\gamma Z}]}{\cos^2\frac{\theta}{2}W_2^{em} + \sin^2\frac{\theta}{2}W_1^{em}}$$

$d(\vec{e},e')X, E_e = 4.867GeV, \theta = 12.9^o$ (PVDIS PRC91 045506 (2015))

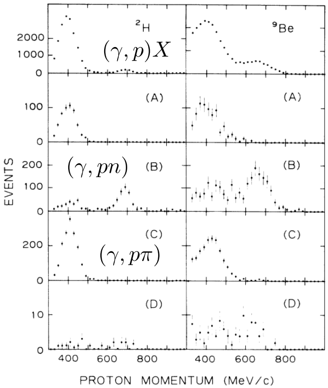


- Pion absorption $\pi + N + N \to N + N$ / Meson Exchange current /Correlation





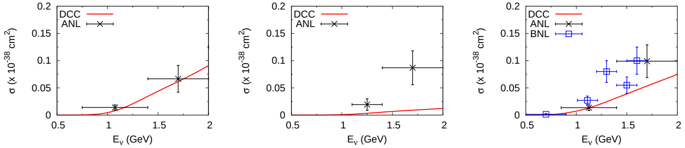
(γ, p) $(E_\gamma = 327\text{MeV})$



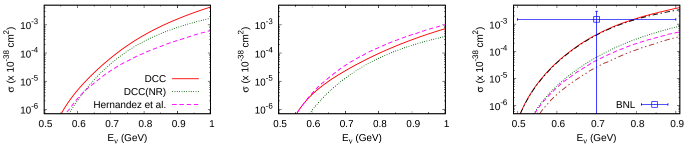
PRC35 Kanazawa et al. (1987)

Neutrino induced two pion production

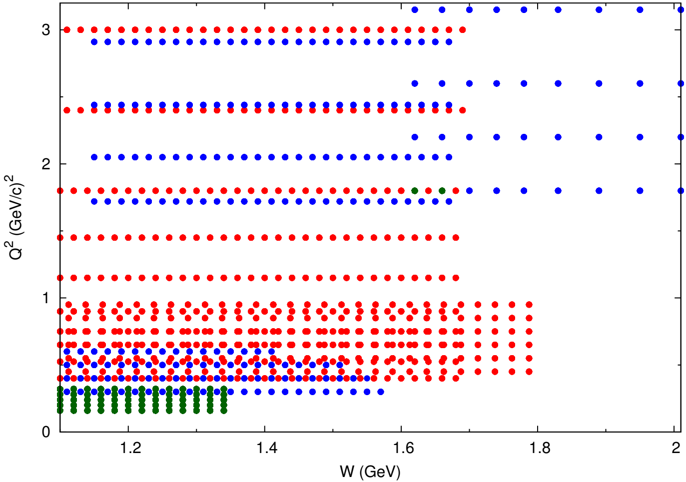
$\nu_\mu p \to \mu^- \pi^+ \pi^- p$ $\nu_\mu p \to \mu^- \pi^+ \pi^+ n$ $\nu_\mu n \to \mu^- \pi^+ \pi^- n$



Near threshold(compare with Hernandez et al.(D(1232)+N(1440))

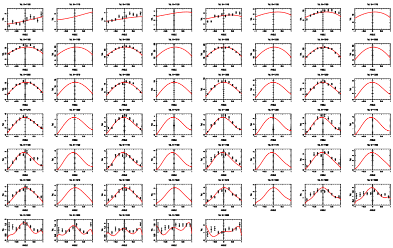


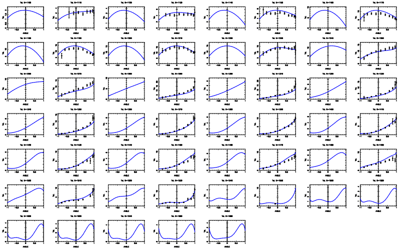
example: single pion electroproduction



CLAS data used in our analysis(red $p(e, e'\pi^0 p)$, blue $p(e, e'\pi^+ n)$, green Both)

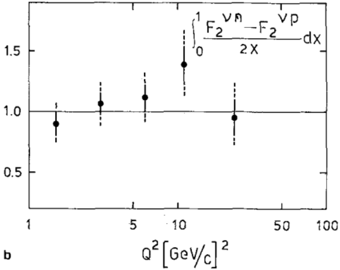
π^0, π^+ electroproduction on proton
($\sigma_T + \epsilon\sigma_L$ for $W = 1.1 - 1.68 GeV$ at $Q^2 = 0.4 (GeV/c)^2$





By fitting single pion production, electromagnetic NN^* transition form factors are obtained.

Adler's sum rule



Right: Z Phys. C28 (1985) Allasia et al.