Neutrino reactions in the nucleon resonance region

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- Collaborators
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  (KEK-theory center collaboration Y. Hayato, M. Hirai, W. Horiuchi, S. Kumano, K. Saito, M. Sakuda)
- Rep. Prog. Phys. **80** 056301,1-38 (2017), S.X. Nakamura et al.
  Prog. Part. Nuc. Phys. **100** 1-68 (2018), L. Alvarez-Ruso et al.

  Phys. Rev. **C88** 035209 1-51 (2013), H. Kamano et al.
  Phys. Rev. **D92** 074024 1-33 (2015), S. X. Nakamura et al.

  Phys. Rev. **C67** 065201 (2003), T. Sato et al.
  Phys. Rev. **D86** 097503 (2012), H. Kamano et al.
  Phys. Rev. **D98** 073001 (2018), J. E. Sobczyk et al.

Contents

- introduction
- models of neutrino reaction in RES
- ANL-Osaka coupled channel model
  brief description of the formalism
  pion, photon, electron induced reaction
  neutrino reaction
- Axial vector current

Neutrino oscillation parameters

- CP violation
- Mass ordering
- improve accuracy of θ_{23}

Experimentally allowed ranges for the oscillation parameters from a global fit to neutrino oscillation data. (Prog. Part. Nucl. Phys. 100(2018)1 Table 1)

angle(degree), Δm^2_{ij}(eV^2), normal ($m_1 < m_2 < m_3$), invertex($m_3 < m_1 < m_2$)

	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

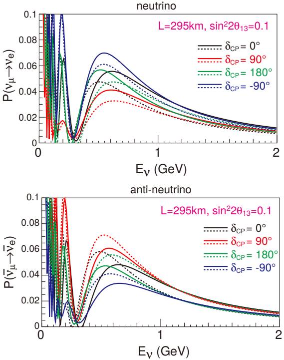
Oscillation probability $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$, expanding in small quantities

$$P_{\mu e} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) + \tilde{J}\,\frac{\Delta_{21}}{A}\,\frac{\Delta_{31}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\mp\delta_{CP} - \frac{\Delta_{31} L}{2}\right),$$

$\Delta_{ij} = \Delta m_{ij}^2 L/2E$, $A = \sqrt{2} G_F N_e$, $s_{ij} = \sin\theta_{ij}$. $\tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{12} \sin^2 2\theta_{23}$, $\tilde{B}_\mp = |A \mp \Delta_{31}|$

- surpression factor θ_{31}, Δ_{21} $\to$ challenging measurement
- matter effects violate CP $\to$ hindering singnal of δ_{CP}
- necessary to identify neutrino flavour and reconstruct neutrino energy $\to$ needs a solid knowledge of neutrino interaction

T2HK and CP



ArXiv:1805.04163 HK Design Report

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim -0.27 \sin\delta_{CP} + 0.09$$

HK Atmospheric neutrino and MH

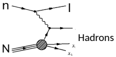
Importance of SIS/DIS in the atmospheric neutrino studies

Compare appearance probabilities of ν_e and $\overline{\nu_e}$

Statistically separate ν_e and $\overline{\nu_e}$

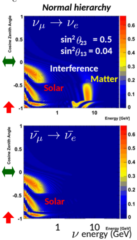
Dominant interaction (a few ~ 10 GeV)

→ Deep inelastic scattering



Differential cross-sections are different

Observables	ν_e CC	$\overline{\nu_e}$ CC
Number of rings	More	Fewer
Transverse momentum	Larger	Smaller
# of decay electrons	More	Fewer
Signal efficiency	52.9%	71%
Purity	58.4%	27.5%



Y. Hayato, NuInt2018 (Gran Sasso)

List of currently operating and future long-baseline neutrino experiments
(Prog. Part. Nucl. Phys. 100(2018)1 Table 2)

Experiment	Baseline	Peak energy	Energy range	Target	Detector	Fiducial Mass
Current:						
T2K	295 km	0.6 GeV	0.3–0.8 GeV	H_2O	WC	22.5 kton
NOvA	810 km	2 GeV	1.5–2.7 GeV	CH_2	Tracking+Calorimetry	13 kton
Future:						
T2HK	295 km	0.6 GeV	0.3–0.8 GeV	H_2O	WC	520 kton
DUNE	1300 km	2 GeV	0.6–3.3 GeV	Ar	Tracking+Calorimetry	40 kton

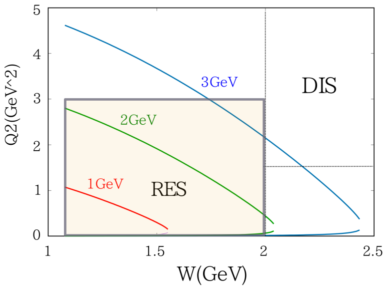
- Importance of knowledge on neutrino reaction in N^*, Δ resonance and DIS region

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}}),$$

NuSTEC(Neutrino Scattering Theory Experiment Collaboration https://nustec.fnal.gov/)

Shallow and Deep Inelastic Scattering(Gran Sasso 2018)
Neutrino-Nucleus Pion Production in the Resonance Region(Pittsburgh 2019)

T2K	$E_\nu \sim$	$0.6 \pm 0.2 (GeV)$
Dune		2 ± 2
atmospheric(MH)		a few ~ 10



$$W = \sqrt{(p+q)^2}, Q^2 = -q^2 = -(p_\nu - p_l)^2$$

Feature of meson production reactions $m_N + m_\pi < W < 2GeV$

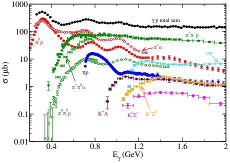
- $\Delta(1232)$ region:

  single pion production, $\Delta(1232)$ dominant mechansim($\nu p \to \mu^- \pi^+ p$)

- Beyond delta resonance:

  Multi-pion(mainly 2π) production including $\eta N, K\Lambda, K\Sigma, , ,$

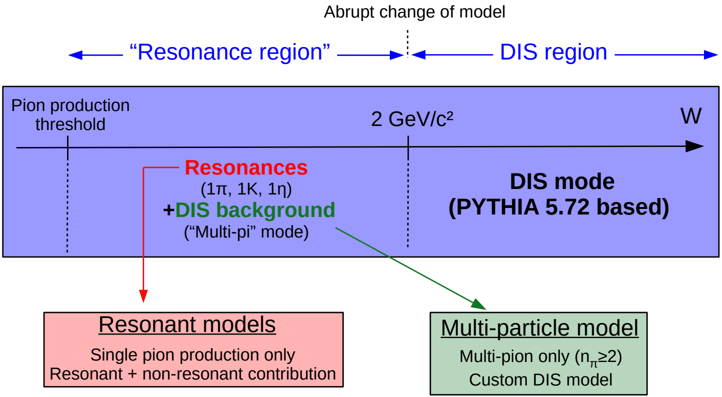
  N^* and Δ resonances $M_R < 2GeV$



- Neutrino event generator (NEUT, GENIE)

  mix Single-pion production (Resonance isobar model) + multi-pion(DIS)

Pion production in the resonance region



No $2\pi/3\pi$ resonances
No DIS contribution to single pion production below W<2 GeV

C. Bronner, NuSTEC workshop pion production 2019,Pittsburgh)

- Isobar model

  neutrino:

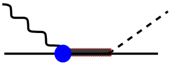
  RS: D. Rein, L. M. Sehgal AP133(81)
  LPP: O. Lalakulich,E.A. Paschos,G. Piranlshvili,PRD74(2006)
  HNV: E. Hernandez,J. Nieves,M. Valverde PRD76(2007)
  R. Gonzales-Jimenes et al. PRD95,113007(2017)+Regge

  pion, photon:Bonn-Gatchina, VPI/GWU, MAID, Jlab/Yerevan .. : amplitudes analysis

- Dynamical coupled channel model

  Neutrino,pion,photon,electron:SL, ANL-Osaka

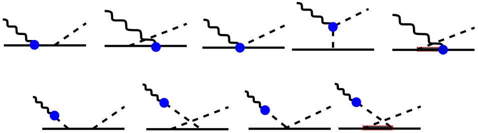
  pion,photon:Jeulich-Bonn, Dubuna-Mainz-Taipei



S-channel Resonance

PDG table
Mass, Width
pion coupling <- Branching ratio
Vector current <- Helicity amplitudes
Axial vector current <- PCAC

+



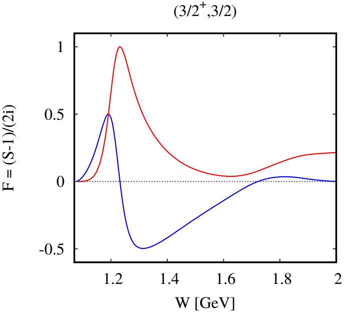
Non-resonant interaction

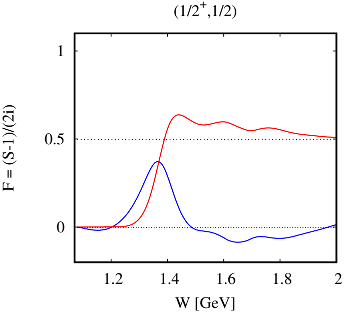
Born Diagrams from Chiral Lagrangian

- Rein-Sehgal model(in generators):
  resonance parameter from PDG + phen. non-resonant mechanism
- Valencia model(E. Hernandez,J. Nieves,M. Valverde):
  $\Delta(1232)$ + non-resonant from chiral L, unitarity correction
- Amplitudes(resonance, non-resonance) of isobar-model have to be tested against data of pion, photon, electron induced meson production reactions

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

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





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

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

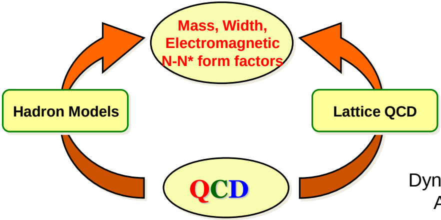
$P_{11} : 1374 - 76i$

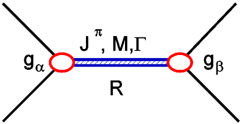
Reaction Data

$$\pi N \rightarrow \pi N,\ \eta N,\ KY,\ \omega N,\ \pi\pi N,\ \ldots$$
$$\gamma^{(*)} N \rightarrow \pi N,\ \eta N,\ KY,\ \omega N,\ \pi\pi N,\ \ldots$$

past two decades,
high precision data from
Jlab,Mainz, Bonn,
GRALL, Spring8

- **Combined analysis of available single pion,eta, kaon production incorporating two pion finat state with Coupled-Channels approach**
- **Extraction of resonance parameters(Mass, transition form factor) from the partial wave amplitudes**





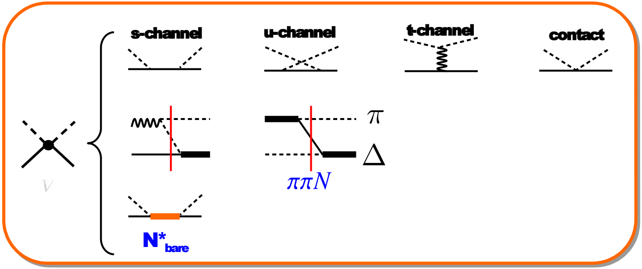
Dynamical Coupled channel approach:
ANL-Osaka, Julich

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.

$$T = V + VG_0T$$

Physics included inside V

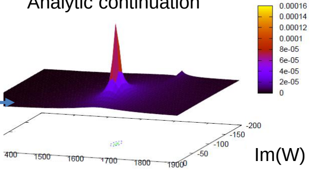


Resonance energy, coupling constants are obtained from the pole of S-matrix:

Partial wave amplitude $\mathcal{F}(W)$

Analytic continuation

Resonance parameter

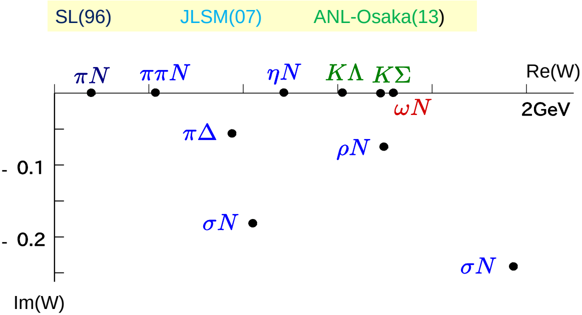


$$< \beta|\mathcal{F}(W)|\alpha > \sim -\frac{R_{\beta,\alpha}}{W - M_{N^*}}$$

mass and width $M_{N^*} = M - i\Gamma/2$

residue $R_{\beta,\alpha}$

coupling constant
helicity amplitude $R_{\beta,\alpha} = g_{\beta,N^*} g_{\alpha,N^*}$



SL :T. Sato,T.-S. H. Lee :PRC54(96),PRC63(01)
JLSM: B.Julia-Diaz,T.-S.H. Lee,A. Matsuyama, T. Sato PRC76,065201(2007)
ANL-Osaka:PRC88,035209 (2013)

channel coupling: unitarity → amplitudes of MB channels are related
signal of resonances might be enhanced at some channel(inelastic reaction)
near threshold of opening channel → a few partial wave, enhanced sensitivity
complex analytic structure of amplitudes

Model for neutrino reaction

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

$$\begin{aligned} J^{\mu}_{em} &= V^{\mu}_3 + V^{\mu}_{IS} \\ J^{\mu}_{CC} &= V^{\mu}_{1+i2} - A^{\mu}_{1+i2} \quad (\Delta S = 0 \text{ current without CKM}) \\ J^{\mu}_{NC} &= V^{\mu}_3 - A^{\mu}_3 - 2\sin^2\theta_W J^{\mu}_{em} - \frac{1}{2}\bar{s}\gamma^{\mu}(1-\gamma_5)s \end{aligned}$$

- 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,T. -S. H. Lee, TS PRC88,035209(2013)

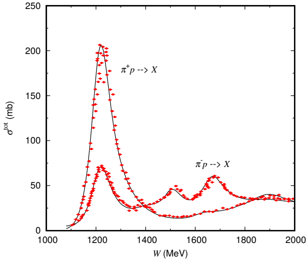
$$\begin{aligned} \pi p &\to \pi N, \eta N, K\Lambda, K\Sigma \\ \gamma p &\to \pi N, \eta N, K\Lambda, K\Sigma \\ ep &\to e'\pi N \end{aligned}$$

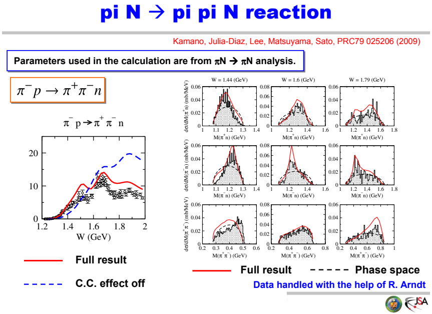
- the model is extended for $\gamma - n$
  H. Kamano,S.X. Nakamura,T.-S. H. Lee,TS PRC94 015291 (2016)
- Axial vector current: $g_A^{NN^*}$ from $g_\pi^{NN^*}$ assuming PCAC and dipole form factor.

  $\to$ Neutrino:S. X. Nakamura,H. Kamano, TS,PRD92 07402(2015)

Pion, photon and Electron induced reaction (DCCmodel)

Total cross section of pion induced reaction

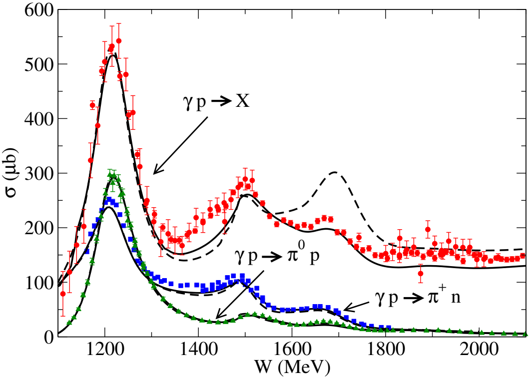




ANL-Osaka Partial-Wave Amplitudes (PWA) H.Kamano, T.-S. Lee, S.X. Nakamura, T.Sato, arXiv:1909.11935v1

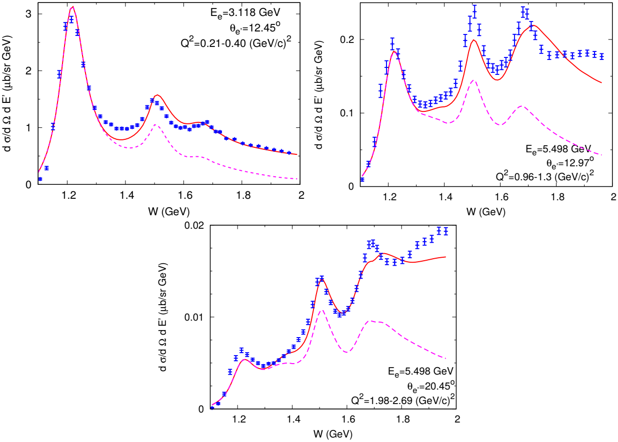
(Right: H. Kamano Baryon2010)

Total cross section of γp



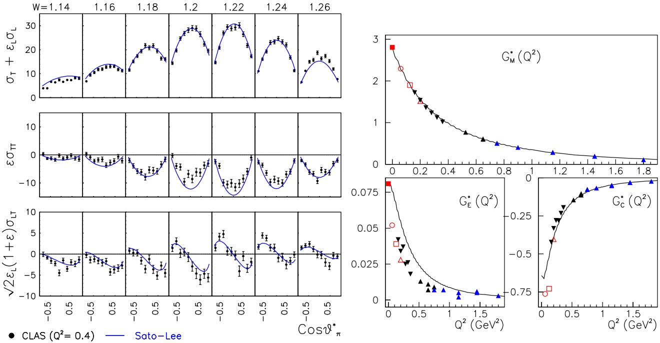
ANL-Osaka Partial-Wave Amplitudes (PWA) H.Kamano, T.-S. Lee, S.X. Nakamura, T.Sato, arXiv:1909.11935v1

Total cross section of $p(e, e')$



ANL-Osaka Partial-Wave Amplitudes (PWA) H.Kamano, T.-S. Lee, S.X. Nakamura, T.Sato, arXiv:1909.11935v1

$$\frac{d\sigma}{dE_{e'}d\Omega_e d\Omega_\pi} = \Gamma[\frac{d\sigma_T}{d\Omega_\pi} + \epsilon\frac{d\sigma_L}{d\Omega_\pi} + \epsilon\frac{d\sigma_{TT}}{d\Omega_\pi}\cos 2\phi_\pi + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{d\Omega_\pi}\cos\phi_\pi]$$

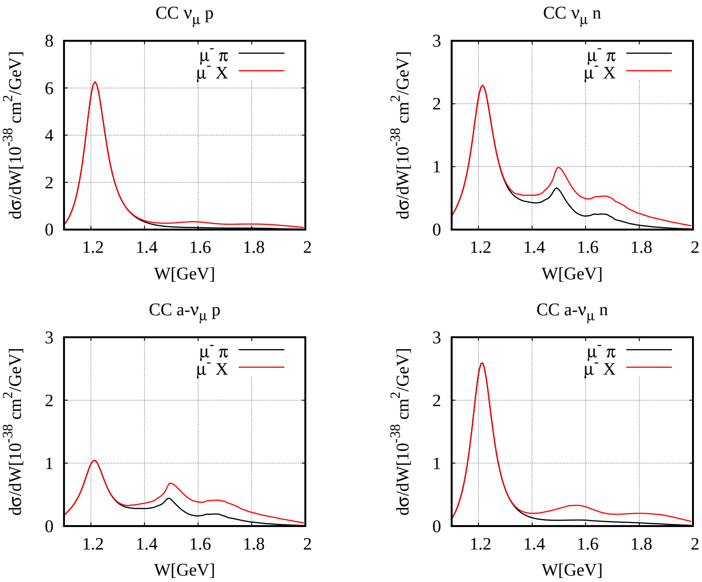


- $\gamma N\Delta$ transition form factors are determined from the angular distribution of pion.

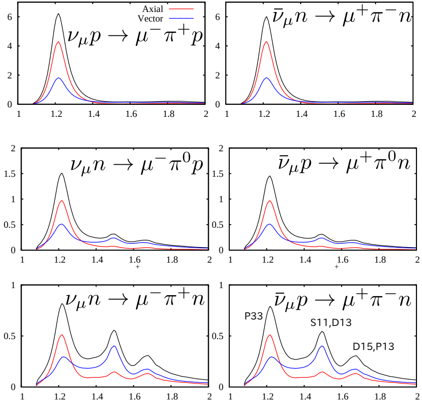
G_M(main term) sensitive to $\frac{d\sigma_T}{d\Omega_\pi} + \epsilon\frac{d\sigma_L}{d\Omega_\pi}$, G_E : $\frac{d\sigma_{TT}}{d\Omega_\pi}$, G_C: $\frac{d\sigma_{LT}}{d\Omega_\pi}$

Neutrino induced reaction

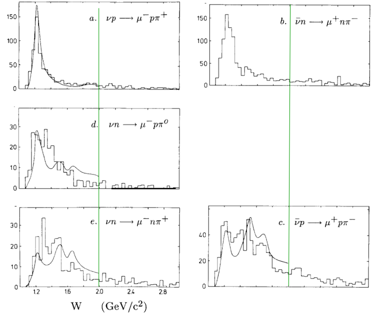
$d\sigma/dW \;\; E_\nu = 2GeV$



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

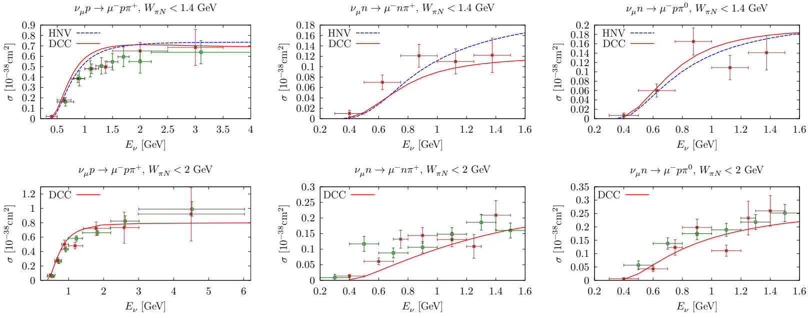


Neutrino anti-neutrino



BEBC NP343,285(1990)

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



J. Sobczyk,E. Hernandez,S.X. Nakamura, J. Nieves,T. Sato PRD98(2018)073001

- Re-analyzed ANL/BNL data, C. Wilkinson et al. PRD90
- ANL-Osaka DCC,PRD92, Hernandez,Nieves,Valverde PRD76

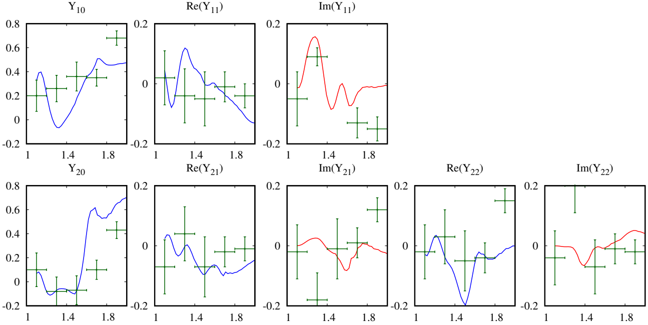
Caution on $\sigma(\nu N)$ of ANL/BNL data extracted from $\sigma(\nu d)$.
About $10 \sim 30\%$ correction due to FSI effects should be corrected S. Nakamura, H. Kamano, T. Sato PRD99,031301(R)(2019)

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

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

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

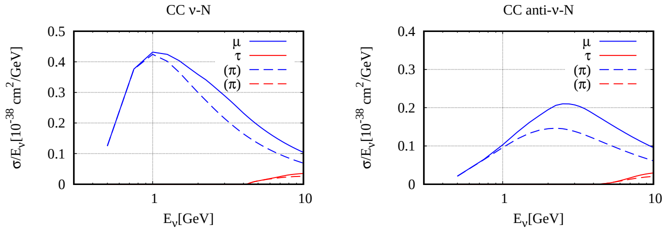
$$\frac{d\sigma}{dW d\Omega_\pi} = \sigma_0 + \sigma_c \cos\phi_\pi + \sigma_s \sin\phi_\pi + \sigma_{2c} \cos 2\phi_\pi + \sigma_{2s} \sin 2\phi_\pi$$



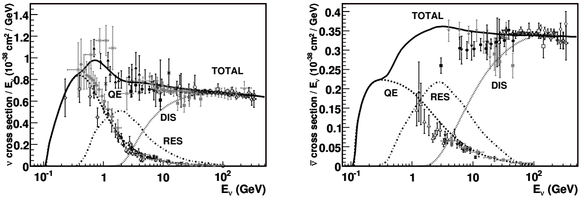
Data:NPB343 (1990)D. Allasia et al.

ANL-Osaka model($W < 2.1GeV$, $Q^2 < 3GeV^2$ (preliminary), nucleon)

Note: in this model, strangeness, charm production is not included.



J. A. Formaggioand G. P. Zeller, Rev. Mod. Phys. 84(2012) 1307

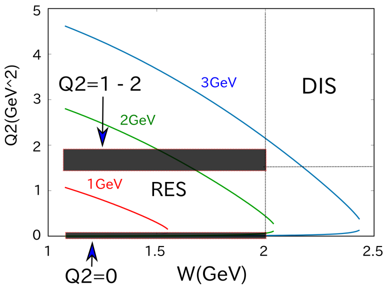


Axial Vector Current

How good our Axial vector current?

- $Q^2 = 0$: data of $\pi - N$ elastic, total cross section
- $Q^2 \sim 1 - 2GeV^2$: Parton model
- Adler's sum rule

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

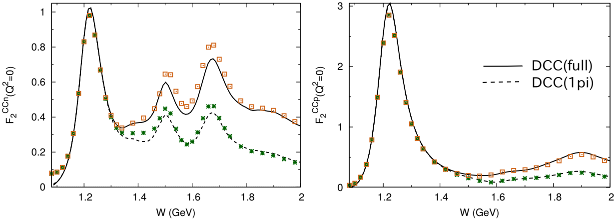


Axial Vector current F_2^{CC} (total cross section) at $Q^2 = 0$

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.

Parton picture vs DCC model

- Parton Picture(Isospin-symmetry, neglect s)

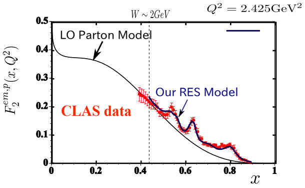
$$
\begin{aligned}
F_2^{EM} &= \frac{x}{2}([(\frac{2}{3})^2 u_p + (\frac{1}{3})^2 d_p] + [(\frac{2}{3})^2 u_n + (\frac{1}{3})^2 d_n]) = x\frac{5}{18}(u+d) \\
F_2^{CC} &= \frac{x}{2}(d_p + d_n)(1+1) = x(u+d) = \frac{18}{5}F_2^{EM}
\end{aligned}
$$

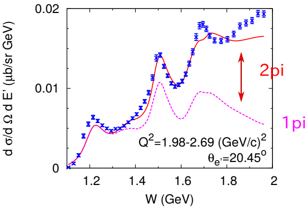
- Hadron picture

$$
\begin{aligned}
F_2^{EM} &\sim \sum_f |< f|V_3 + V_{IS}|N > |^2 \\
F_2^{CC} &\sim \sum_f [|< f|V_{1+i2}|N > |^2 + |< f|A_{1+i2}|N > |^2]
\end{aligned}
$$

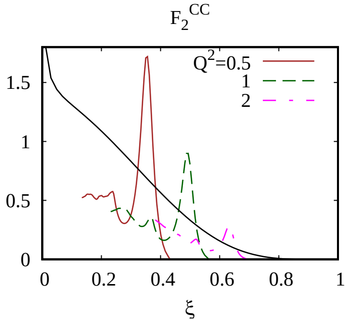
Does DCC model describe boundary between RES and DIS ?

- Electromagnetic structure function of proton



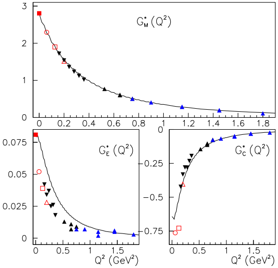


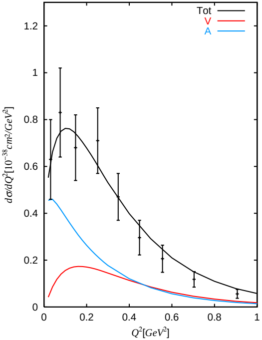
- Charged Current $[F_{2p}^{CC} + F_{2n}^{CC}]/2$



- Missing Strength in higher W region
- around $W \sim 2GeV, Q^2 = 1 \sim 2GeV^2$, $F_2^{CC} \sim |V|^2$.
- Question on Quark-Hadron duality in neutrino reaction
  PRC 75 015202(2007), Lalalulich et al.

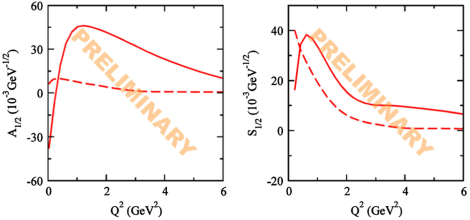
$\Delta(1232)$: Left Electron Scattering(EM), Right Neutrino reaction(CC)





PRC75,015205(2007)(EM), PRC67,65201 (2003)(CC)

- Vector(EM): Helicity amplitudes extracted from the residue of partial wave amplitude(DCC-model) at resonance pole (figure from H. Kamano)



- Axial Vector (Quark model)

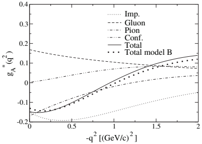
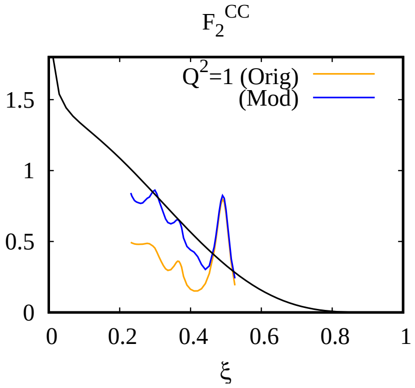


FIG. 7. Axial form factor $g_A^*(q^2)$. Notation as in the upper panel of Fig. 3.

PRC75,065203 (2007) D. Barquilla-Cano, A.J. Buchmann, E. Hernandez

$$A_A^\lambda(Q^2) = A_A^\lambda(0) \times \frac{A_V^\lambda(Q^2)}{A_V^\lambda(0)} \quad \text{except} \quad P_{33}$$

Modify Q^2 dependence of axial N-'bare' resonance form factor. (Meson cloud part is not modified)



preliminary

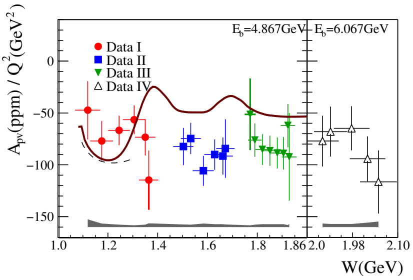
Parity Violating Asymmetries

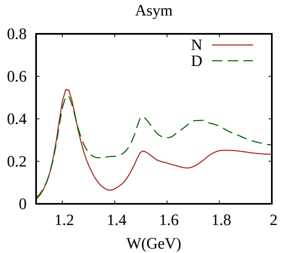
Parity violating asymmetry of $d(\vec{e}, e')$ reaction

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

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

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





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

- https://www.phy.anl.gov/theory/research/anl-osaka-pwa
  - Resonance parameters(Pole position, residue, helicity amplitudes)
  - Partial wave amplitudes $\pi, \gamma, \gamma^* N \to \pi N, \eta N, K\Lambda, K\Sigma$ and $\pi N \to \sigma N, \rho N, \pi\Delta$
- Tables of Structure functions $W_i(W, Q^2)$ for EM,CC,NC

$$\frac{d\sigma}{d\Omega_{l'} dE_{l'}} = \frac{G_F^2 C_\alpha^2 |\boldsymbol{p}_l| E_l}{2\pi^2} \Big[2W_1 \sin^2\frac{\chi}{2} + W_2 \cos^2\frac{\chi}{2} \pm \frac{W_3}{M_N}\left((E_\nu + E_l)\sin^2\frac{\chi}{2} - \frac{m_l^2}{2E_l} \right) + \frac{m_l^2}{M_N^2} W_4 \sin^2\frac{\chi}{2} - \frac{m_l^2}{M_N E_l} W_5 \Big]$$

$C_\alpha = V_{ud}^2/(1+Q^2/m_W^2)$ $[C_\alpha = 1/(1+Q^2/m_Z^2)]$ for CC [NC]. $\cos\chi = |\boldsymbol{p}_l|/E_l \cos\theta_l$

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.
  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.
  Comparison with PDF at high Q^2, suggests need for more strength at high W region.
  Improvement of axial transition form factors is important.
  PV asymmetry , in principle, gives information of axial vector current.