Neutrino Induced Meson Production Reaction

DCC(coupled channel) model

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Contents

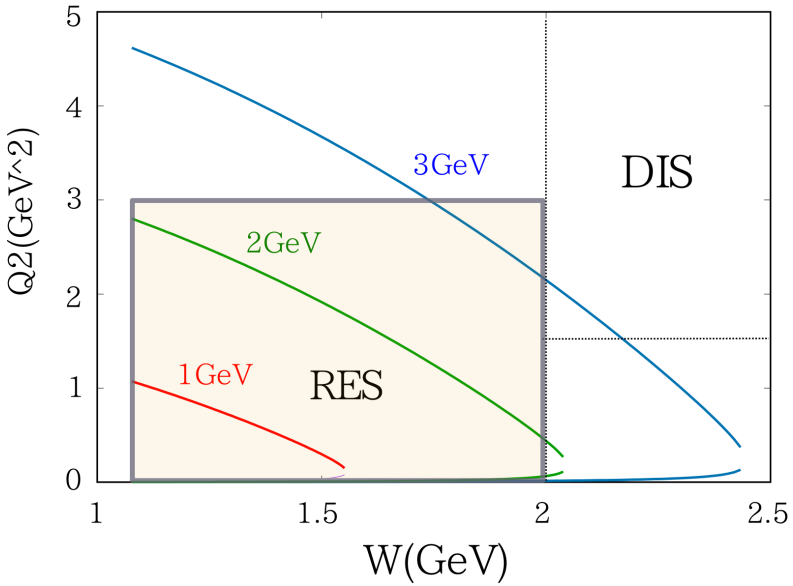
- Motivation
- Coupled channel model of electroweak meson production reaction
- Pion, photo and electroproduction of meson
- Neutrino reaction
- Axial vector form factors of nucleon resonances
- Summary

Collaborators: S.X. Nakamura, H. Kamano, T. -S. H. Lee
N. Suzuki, A. Matsuyama, B. Julia-Diaz

JSPS:16K05354,19H05104,25105010

Motivation: GeV neutrino reaction

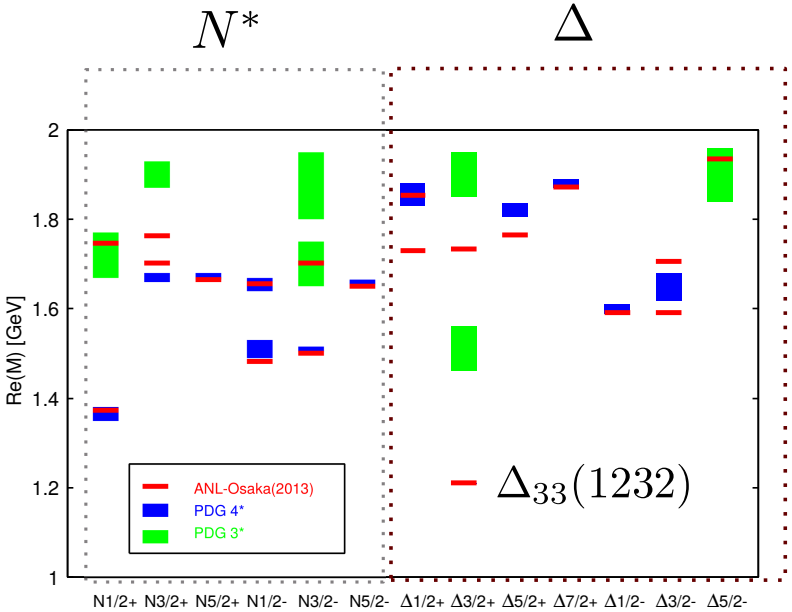
T2K	$E_\nu \sim$	$0.6 \pm 0.2 (GeV)$
Dune		2 ± 2
atmospheric(MH)		a few ~ 10

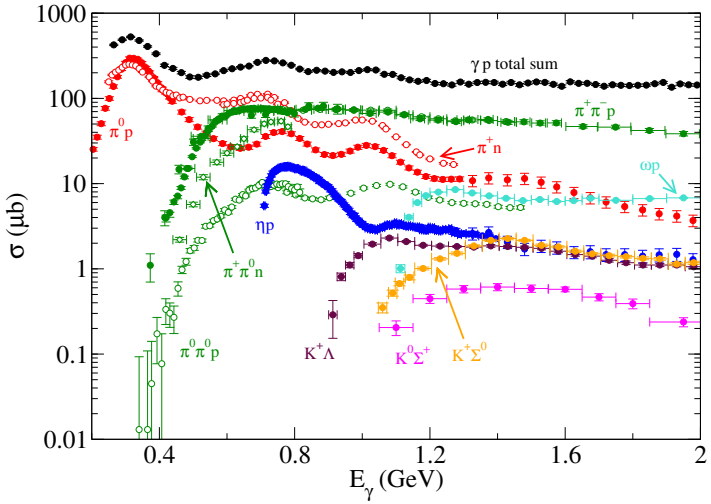


$$W = \sqrt{(p+q)^2}, Q^2 = -q^2 = -(p_\nu - p_l)^2$$

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

- meson production through N^* and Δ resonances $M_R < 2GeV$ and non-resonant mechanism.





- opening of $\eta N, \pi\pi N, K\Lambda, K\Sigma, , ,$ channels
  $\rightarrow$ multi-channel unitarity including three-body($\pi\pi N$).

Brief summary:Models of neutrino induced pion production

Summary of models for neutrino reaction in RES

	Res	Non-res	Unit.	1pi	2pi	Tot
RS	Delta,N*	-	X	O		O
LPP	Delta,N*	X	X	O		O
HVM	Delta(1232)	chiral	O	O		
	Delta(1232)+N(1440)	chiral	X	O	O	
Giessen	Delta, N*	phen.	X	O		O
ANL-Osaka	Delta, N*	O	O	O	O	O

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) Giessen: T. Leitner,O.Buss,L.Alvarez-Ruso,U. Mosel,PRC79(2009)
ANL-Osaka DCC:S.X.Nakamura,H. Kamano,TS,PRD92(2015) ,TS,D. Uno,T.-S.H.Lee PRC67(2003)

R. Gonzales-Jimenes et al. PRD95,113007(2017)+Regge

reaction models

- Isobar model

  Most of the reaction models of neutrino inducde meson production

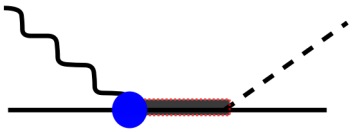
  pion, photon:Bonn-Gatchina, VPI/GWU, MAID, Jlab/Yerevan .. : amplitudes analysis

- Dynamical coupled channel model

  ANL-Osaka

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

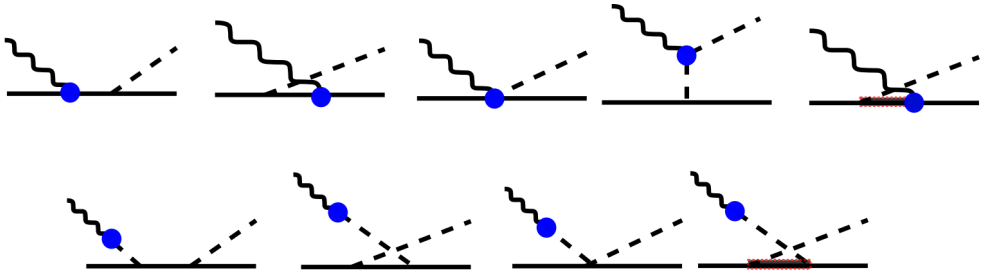
Isobar model



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

- amplitudes(resonance, non-resonance) have to be tested against data of pion, photon, electron induced meson production reactions

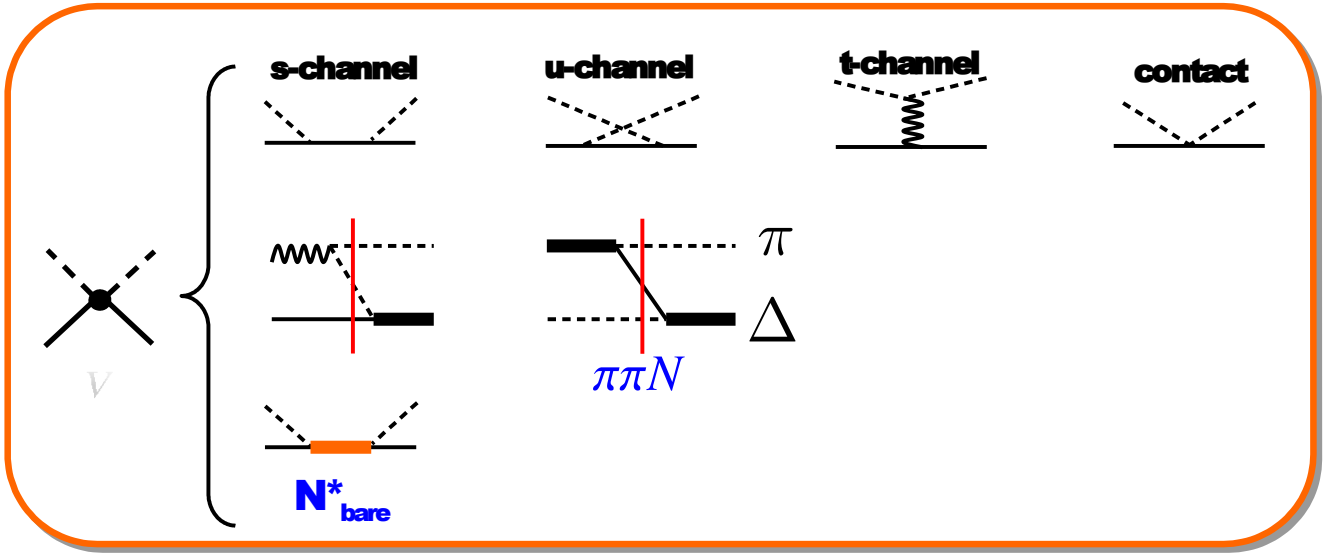
ANL-Osaka DCC model

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.

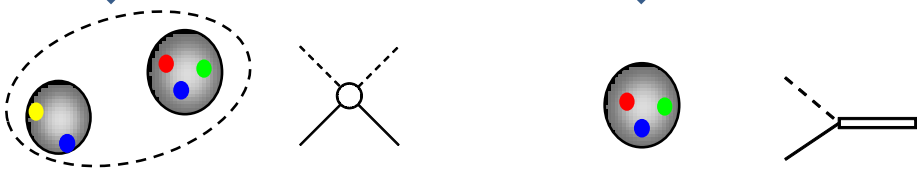
$$T = V + VG_0T$$

Physics included inside V



$$T_{\alpha,\beta}(W) = t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \bar{\Gamma}_{\alpha,i}(W)[\frac{1}{W - m_0 - \Sigma(W)}]_{ij}\bar{\Gamma}_{\beta,j}(W)$$

α, β Meson-Baryon channel i, j Resonances



•Pole of t^{nr} does not appear in full T (Doring et al. 2009)

•Determinant of N* green function gives resonance position
(analytic continuation by deforming contour of momentum integral)

$$Det[(W - m_0 - \Sigma(W))_{ij}]$$

•Resonance form factors from residue of amplitude MB

$$A_\lambda = < \tilde{\phi}_R | j_{em} | N > = \frac{1}{\sqrt{1 - d\Sigma/dW}} \bar{\Gamma}(M - i\Gamma/2)$$

$$\bar{\Gamma}(W) = (1 + t^{nr}(W) G^0(W))\Gamma$$

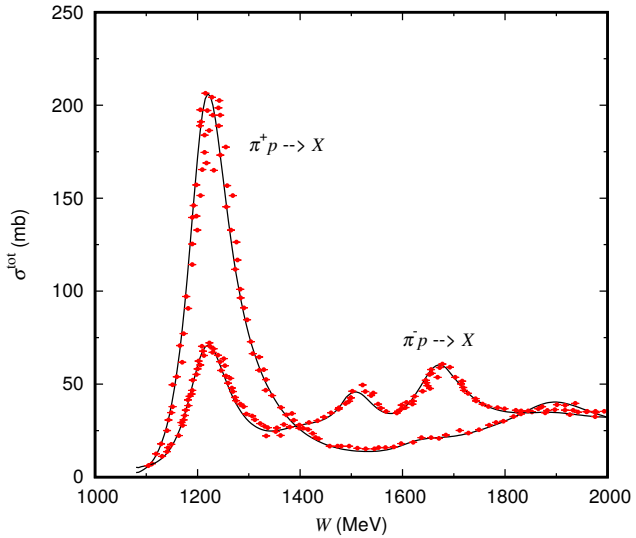
- The model is constructed by fitting available data on pion, photon, electron induced meson production reaction(two-body final state). (Recent model: H. Kamano,S.X. Nakamura L, TS PRC88,035209(2013)

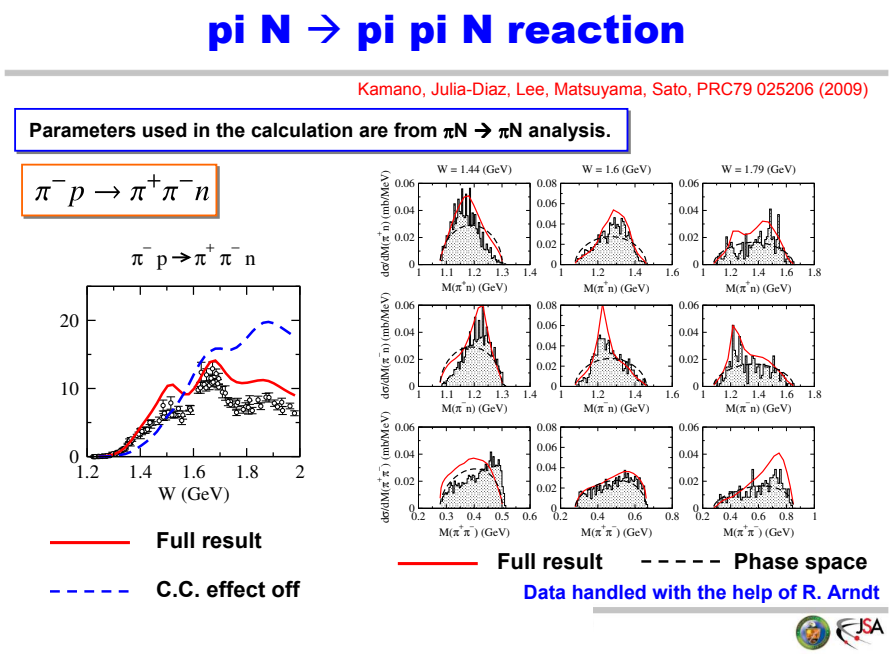
$$\begin{aligned} \pi p &\rightarrow \pi N, \eta N, K\Lambda, K\Sigma \\ \gamma p &\rightarrow \pi N, \eta N, K\Lambda, K\Sigma \\ ep &\rightarrow e'\pi N \end{aligned}$$

- 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)
- 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.)

Pion, photon and Electron induced reaction (DCCmodel)

Total cross section of pion induced reaction

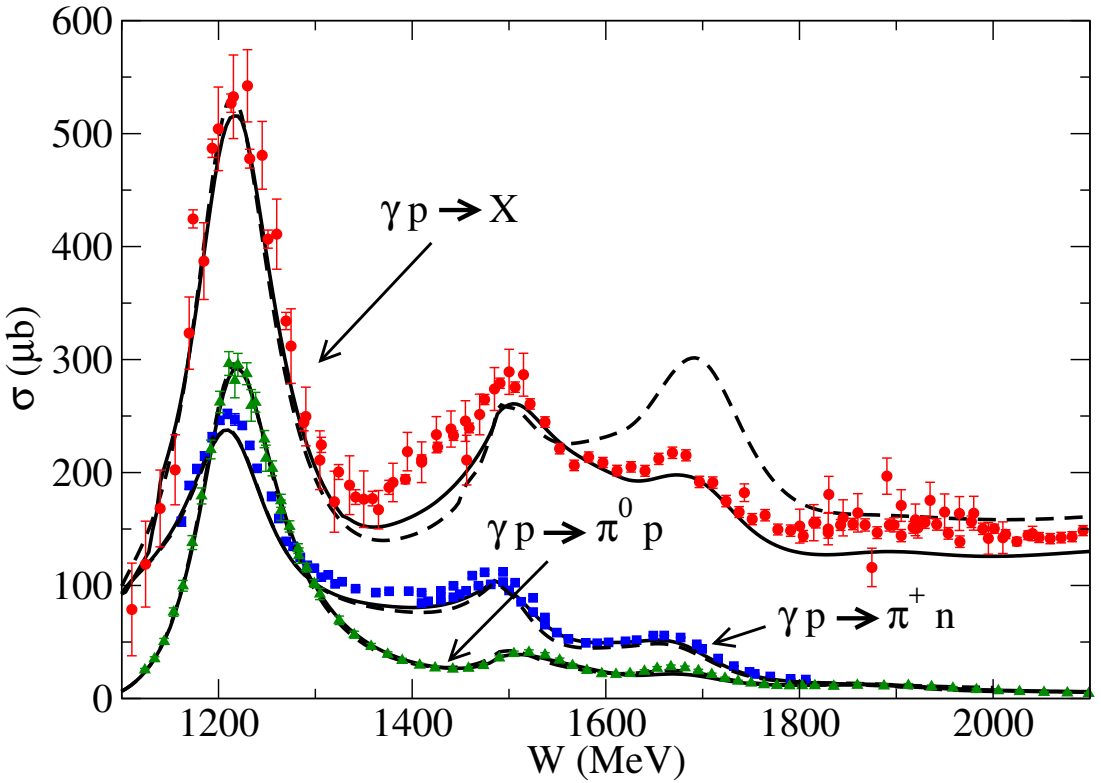




ANL-Osaka Partial-Wave Amplitudes (PWA) H.Kamano, T.-S. Lee, S.X. Nakamura, T.Sato, arXiv:1909.11935v1

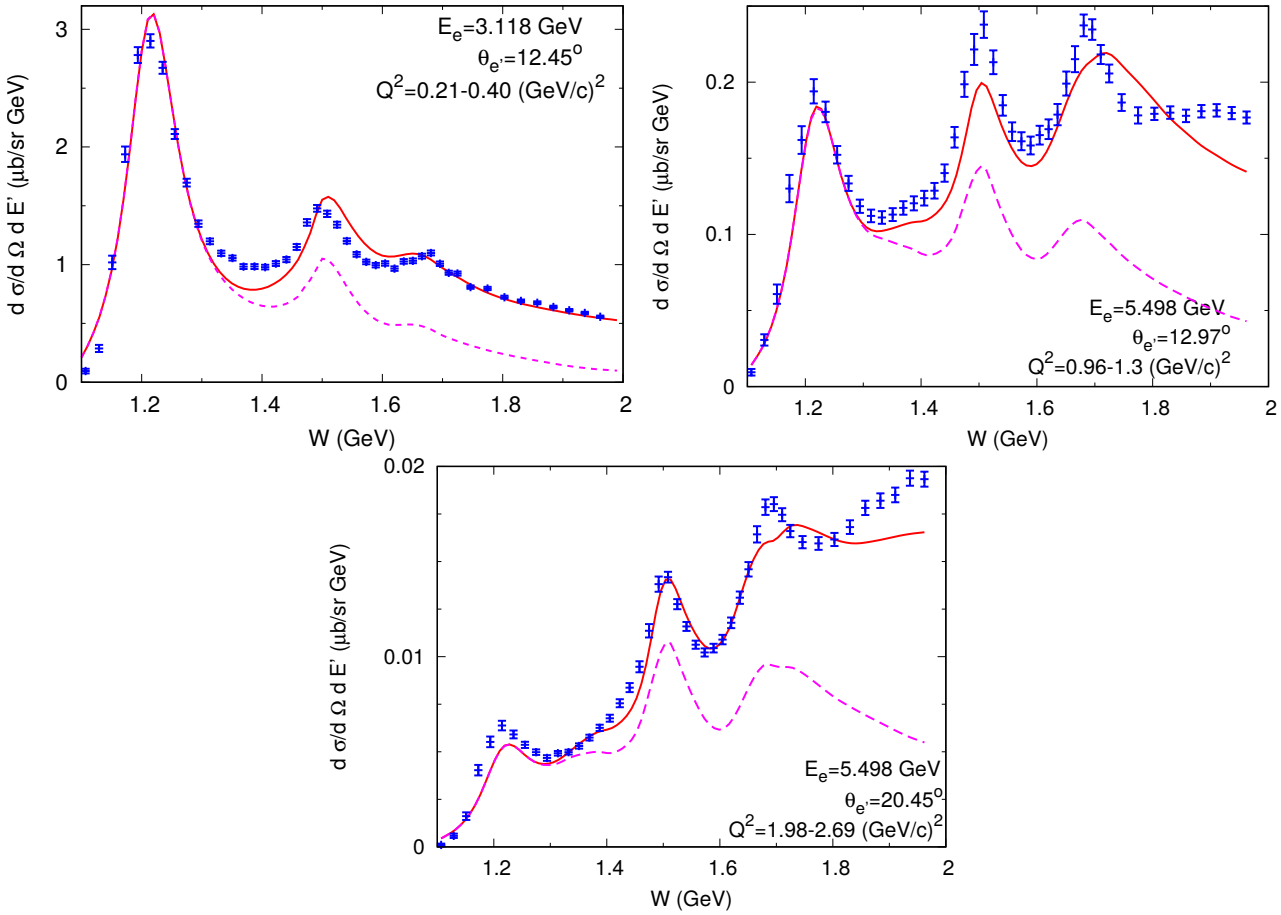
(Right: H. Kamano Baryon2010)

Total cross section of γp



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

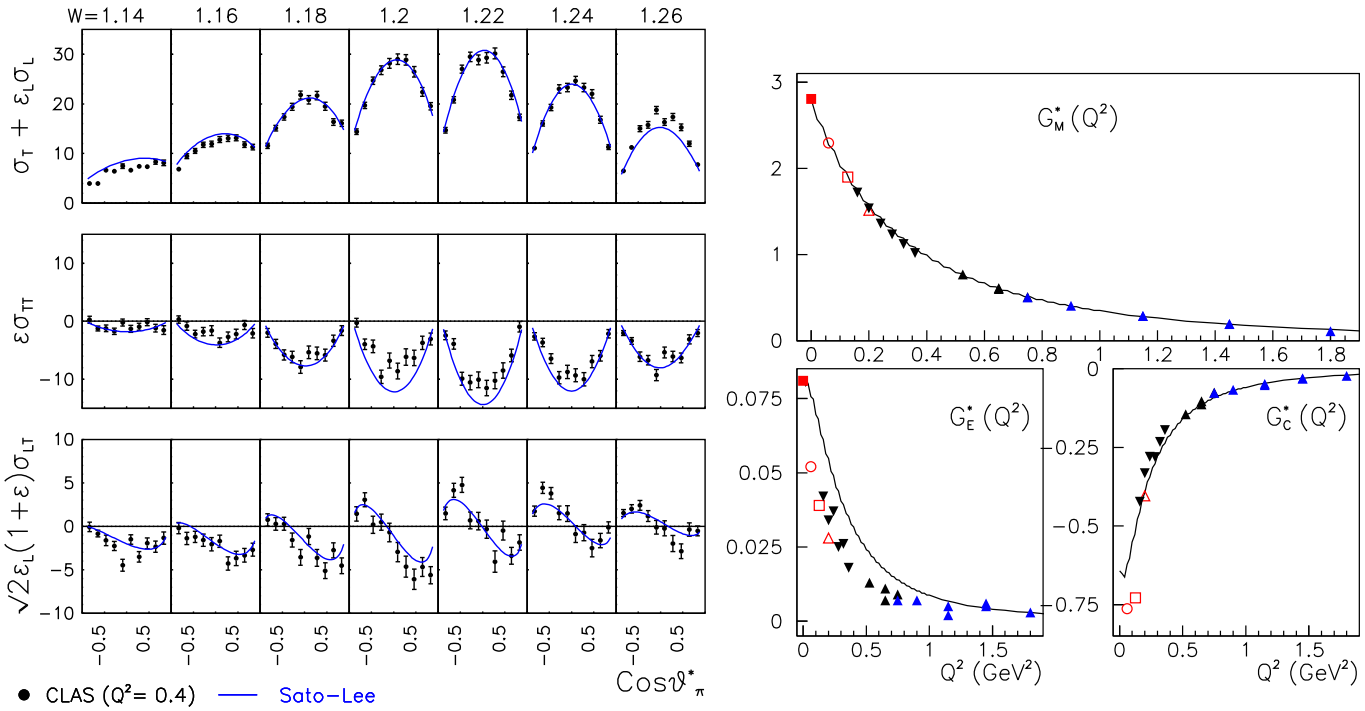
Total cross section of $p(e, e')$



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

Angular distribution of pion

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

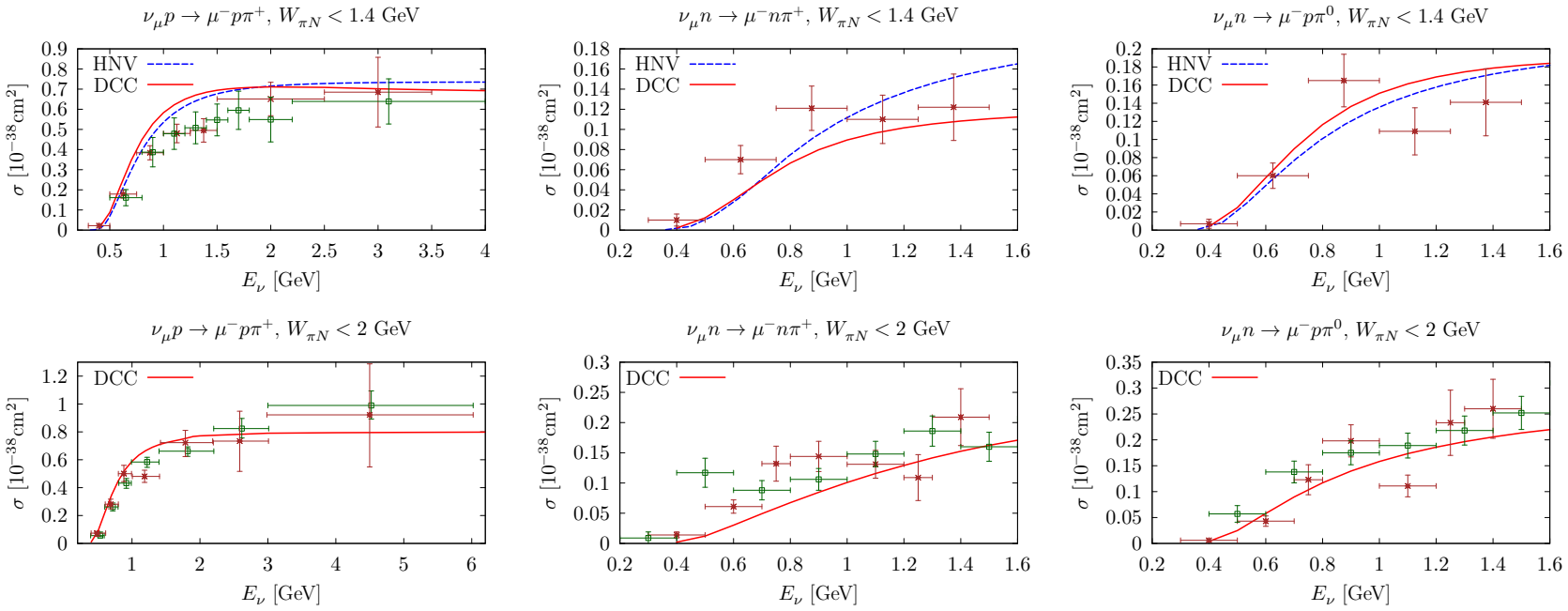


- $\gamma N\Delta$ transition form factors are determined from the angular distribution of pion.

  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

Single pion production in $\Delta(1232)$ region



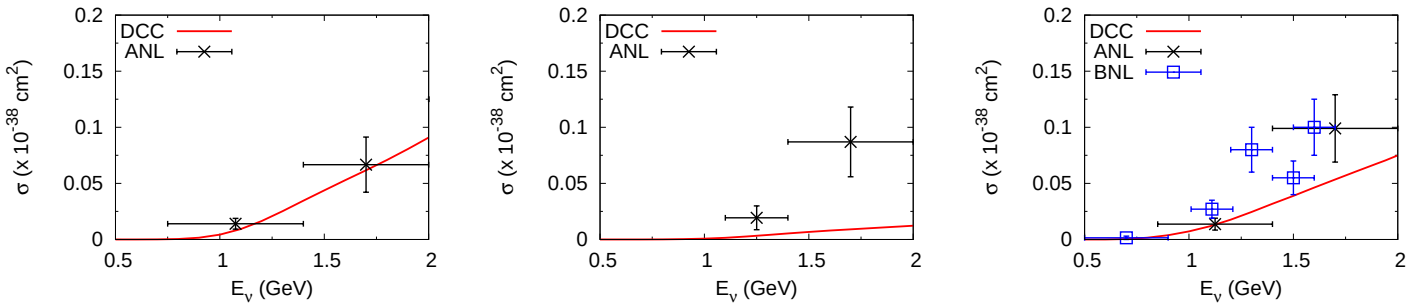
J. Sobczyk,E. Hernandez,S.X. Nakamura, J. Nieves,T. Sato PRD98(2018)073001

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

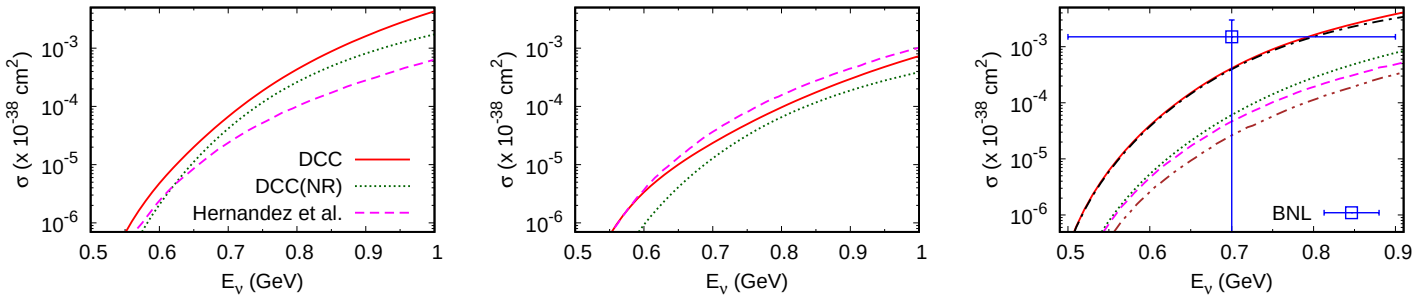
Caution on $\sigma(\nu N)$ of ANL/BNL data extracted from $\sigma(\nu d)$.
About $10 \sim 30\%$ correction due to FSI effects should be corrected S. Nakamura, H. Kamano, T. Sato PRD99,031301(R)(2019)

Neutrino induced two pion production

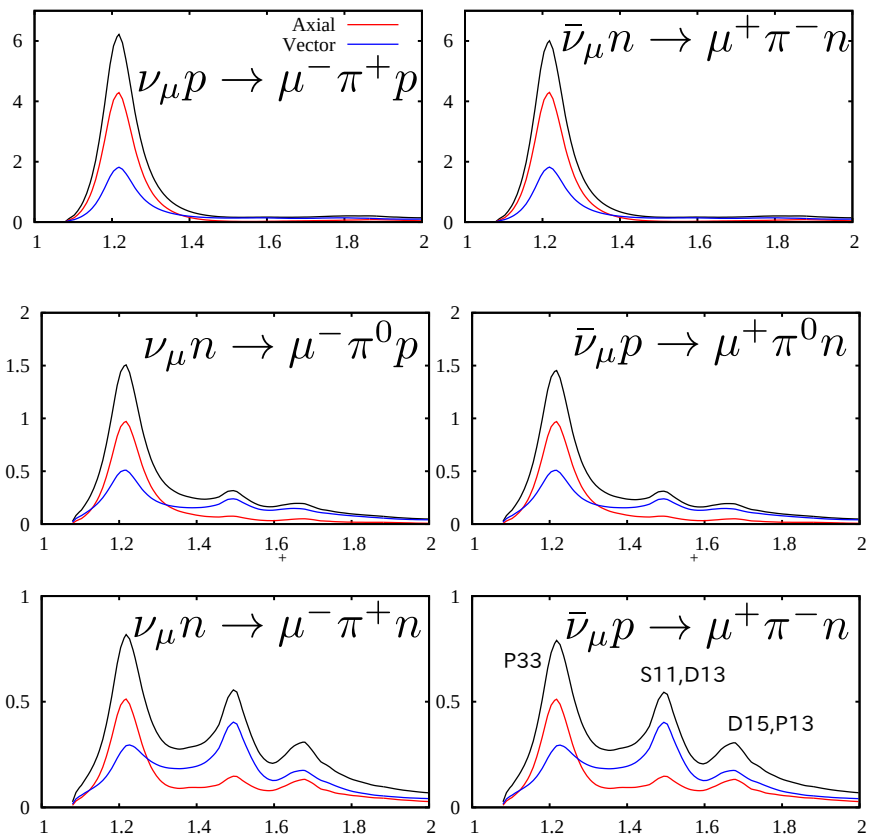
$\nu_\mu p \to \mu^- \pi^+ \pi^- p$ $\nu_\mu p \to \mu^- \pi^+ \pi^+ n$ $\nu_\mu n \to \mu^- \pi^+ \pi^- n$



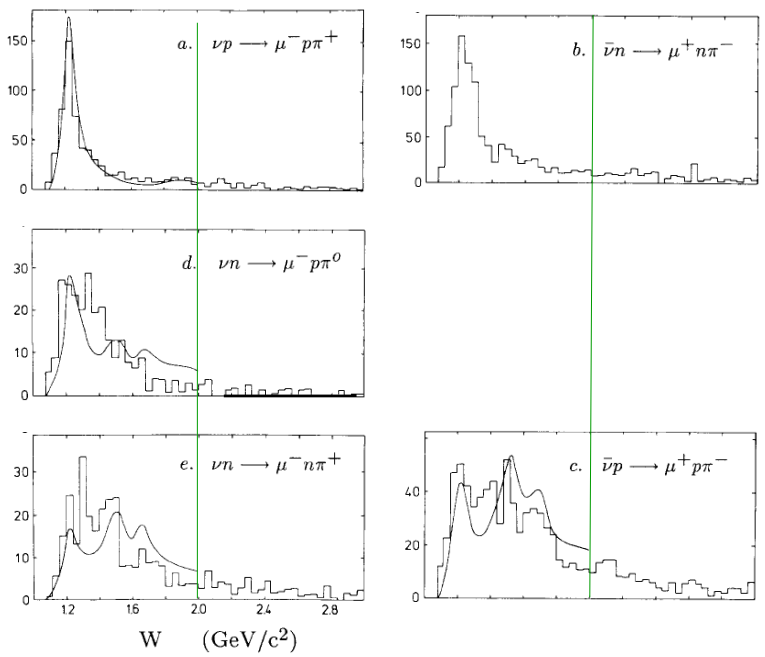
Near threshold(compare with Hernandez et al.(D(1232)+N(1440))



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



Neutrino anti-neutrino

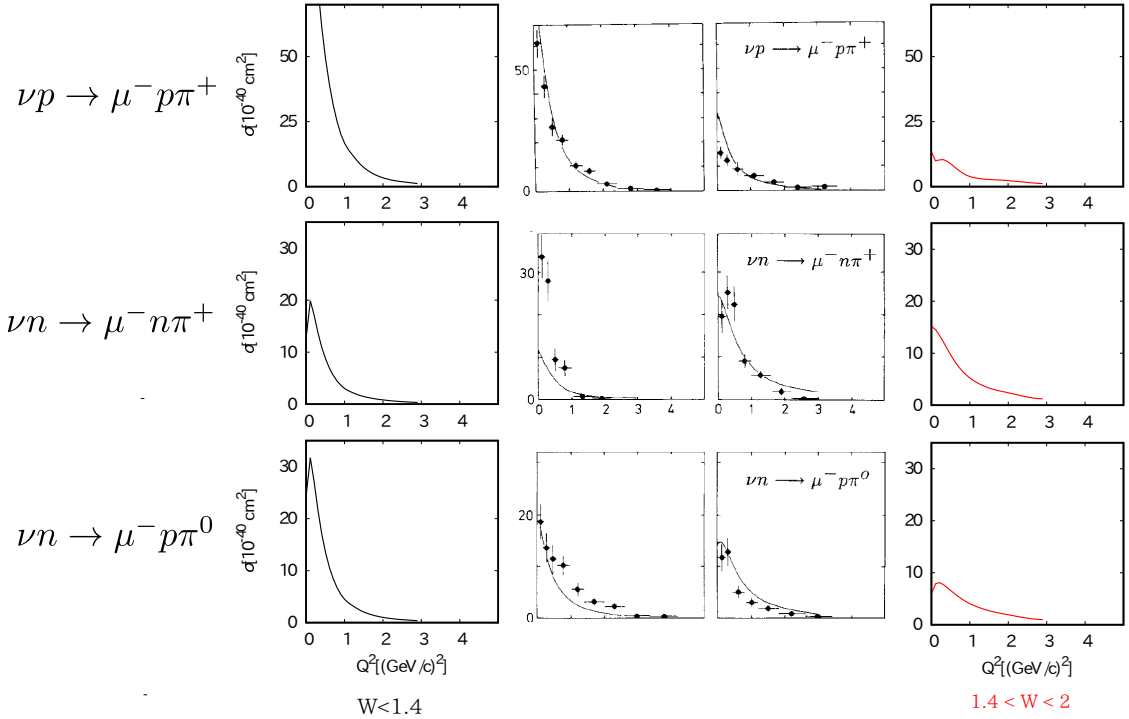


BEBC NP343,285(1990)

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

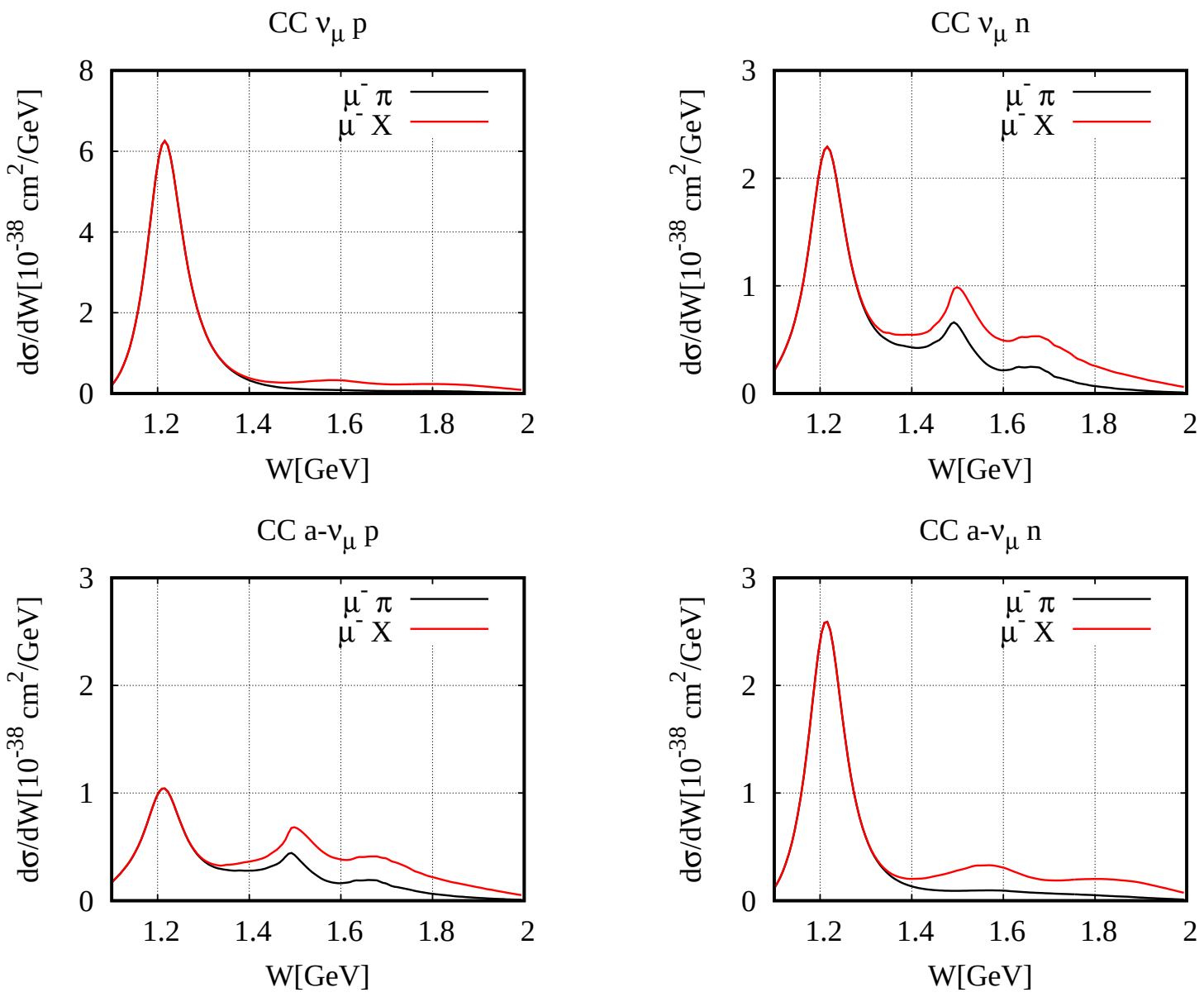
Q^2 distibution and strength of higher W

ANL-Osaka DCC model(preliminary)



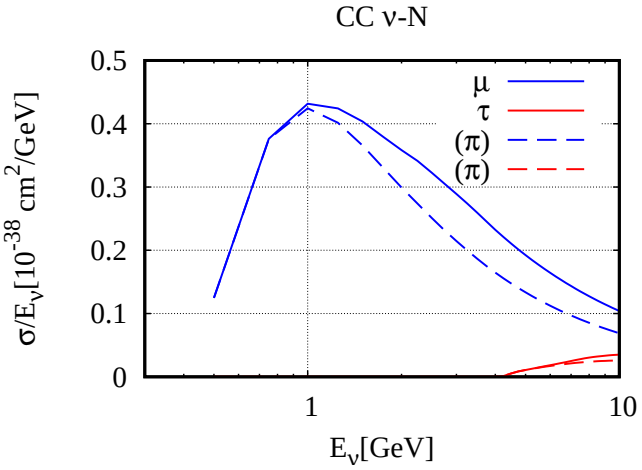
- Reasonable description of single pion production for $W > 1.4GeV$ with DCC model.

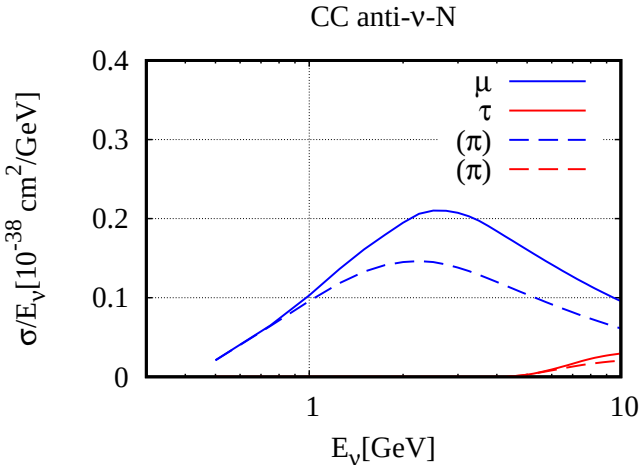
$d\sigma/dW \;\; E_\nu = 2GeV$



$(\sigma_p + \sigma_n)/2E_\nu$

$W < 2.1GeV$, $Q^2 < 3GeV^2$ (preliminary)





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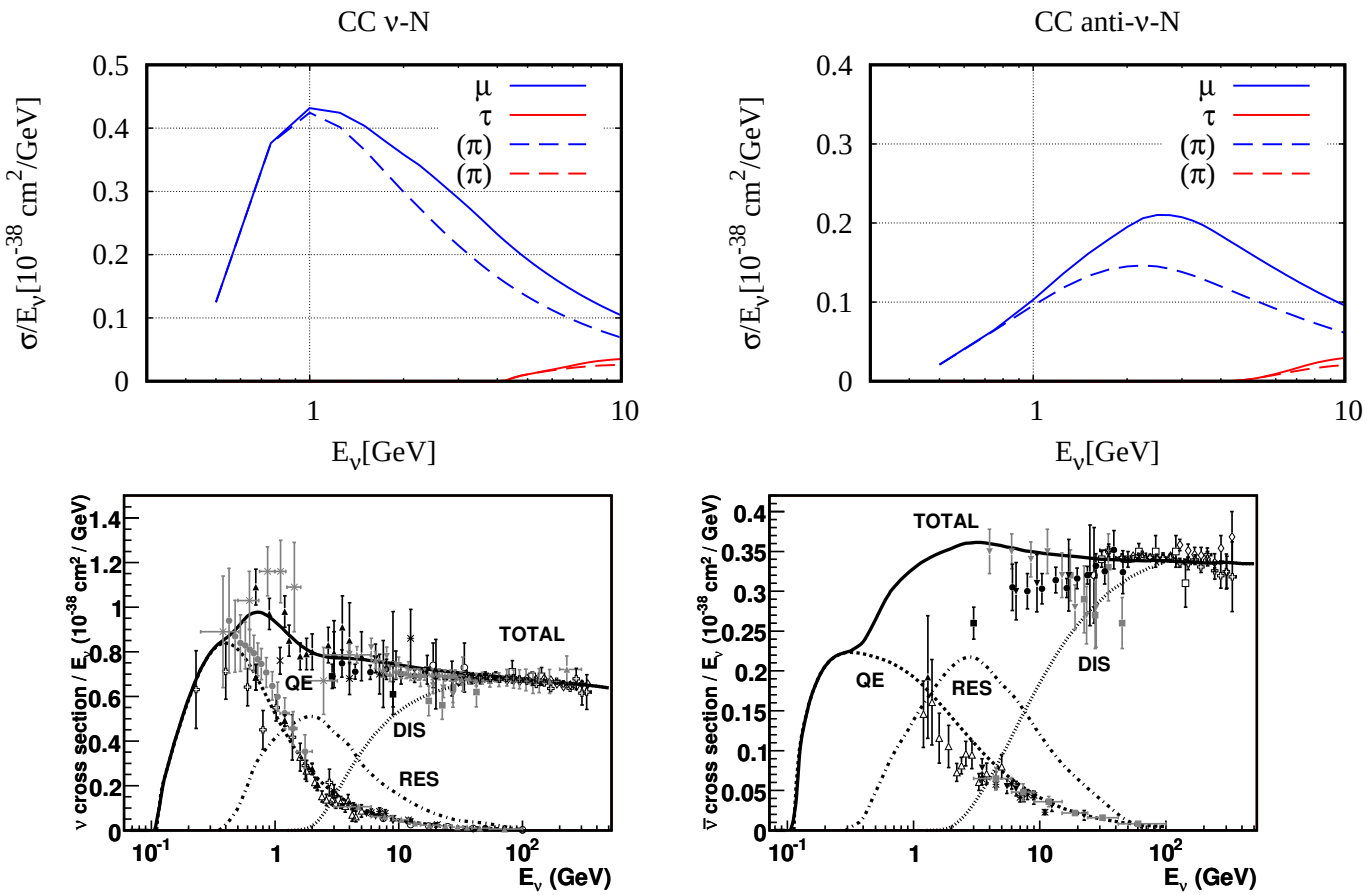
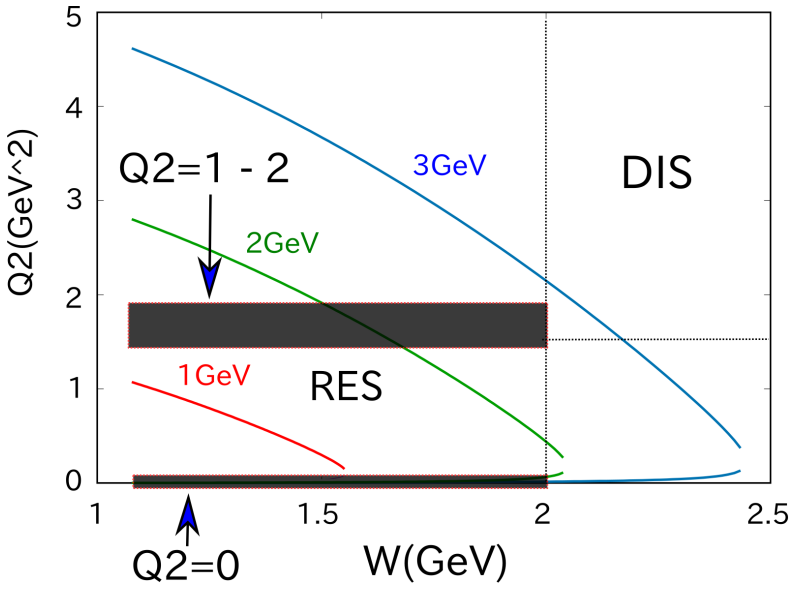


Axial Vector Current

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



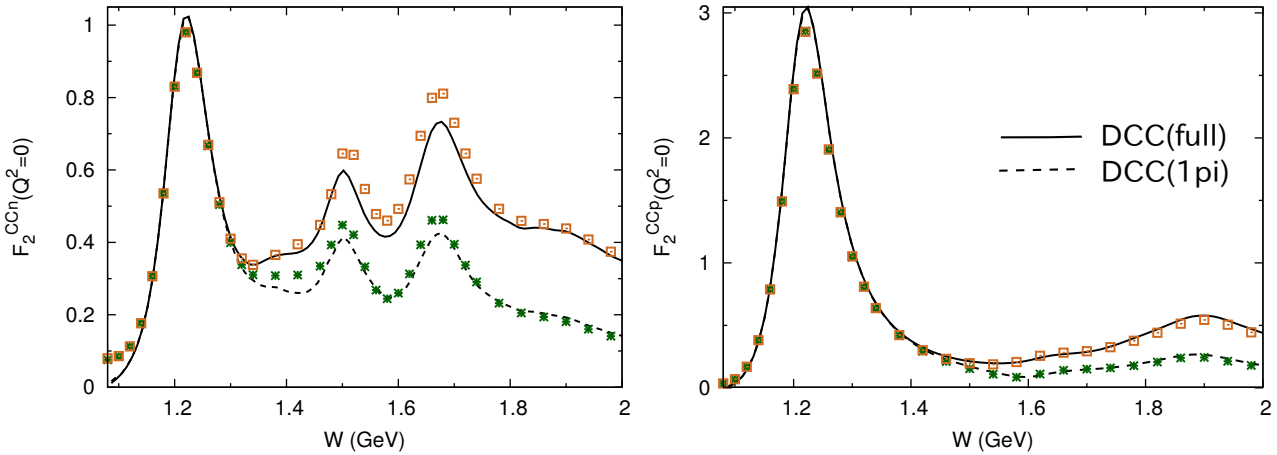
F_2^{CC} and pi-N cross section ($Q^2 = 0$)

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 Distribution vs DCC model

- Parton Picture(Isospin-symmetry, neglect s)

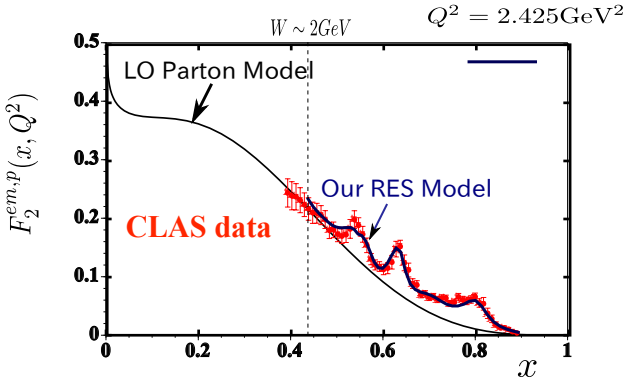
$$
\begin{aligned}
F_2^{EM} &= \frac{x}{2}([(\frac{2}{3})^2 u_p + (\frac{1}{3})^2 d_p] + [(\frac{2}{3})^2 u_n + (\frac{1}{3})^2 d_n]) = x\frac{5}{18}(u+d) \\
F_2^{CC} &= \frac{x}{2}(d_p + d_n)(1+1) = x(u+d) = \frac{18}{5}F_2^{EM}
\end{aligned}
$$

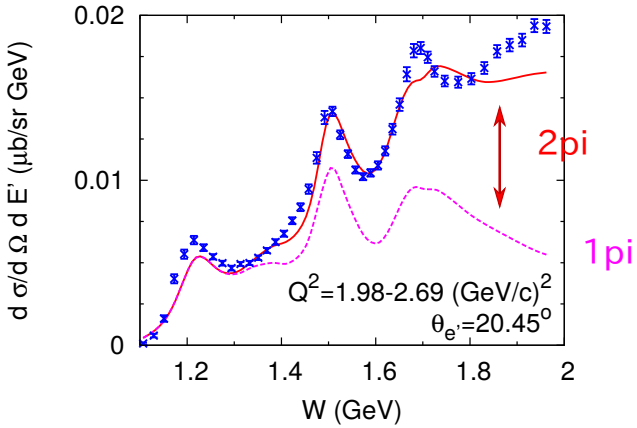
- Hadron picture

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

Does DCC model describe boundary between RES and DIS ?

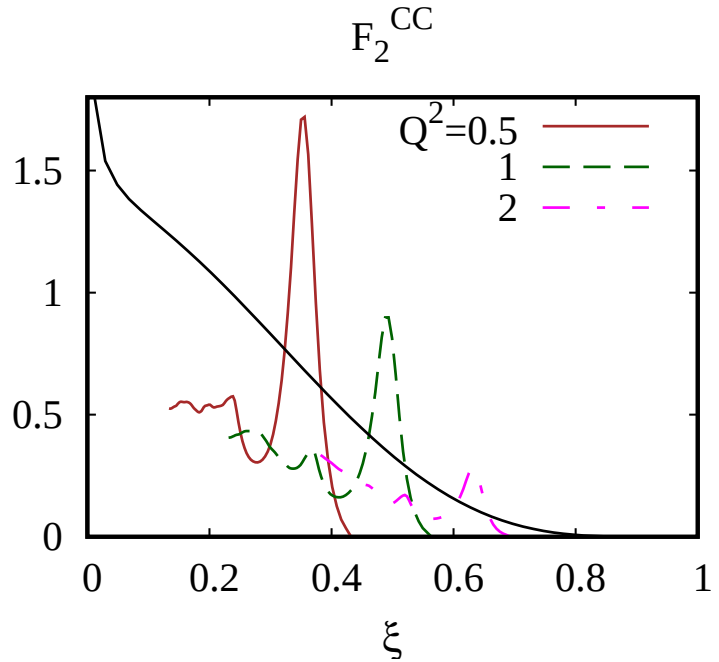
- Electromagnetic structure function of proton





Does DCC model describe boundary between RES and DIS ?

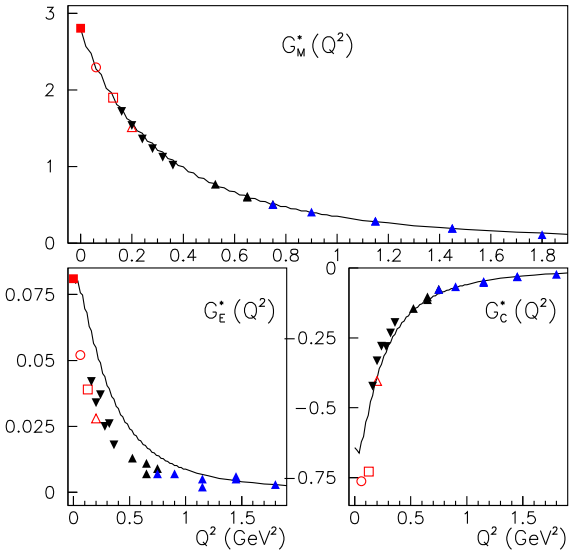
- Charged Current $[F_{2p}^{CC} + F_{2n}^{CC}]/2$

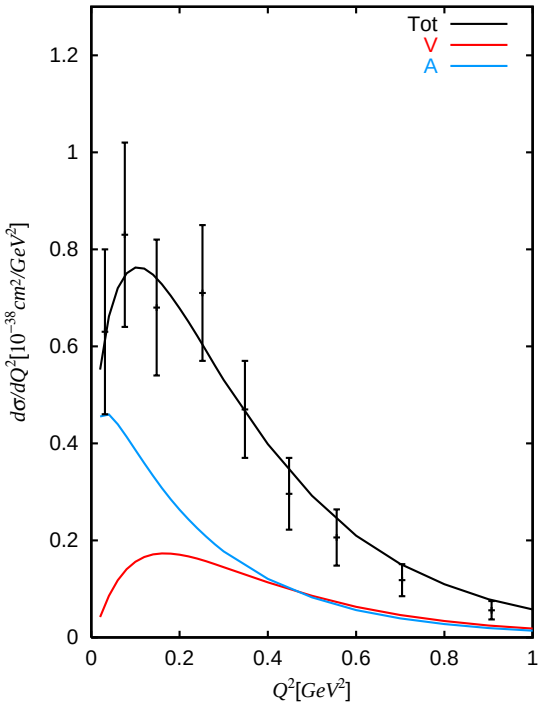


around $W \sim 2GeV, Q^2 = 1 \sim 2GeV^2$, $F_2^{CC} \sim |V|^2$.

Possible solution: transition form factor

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

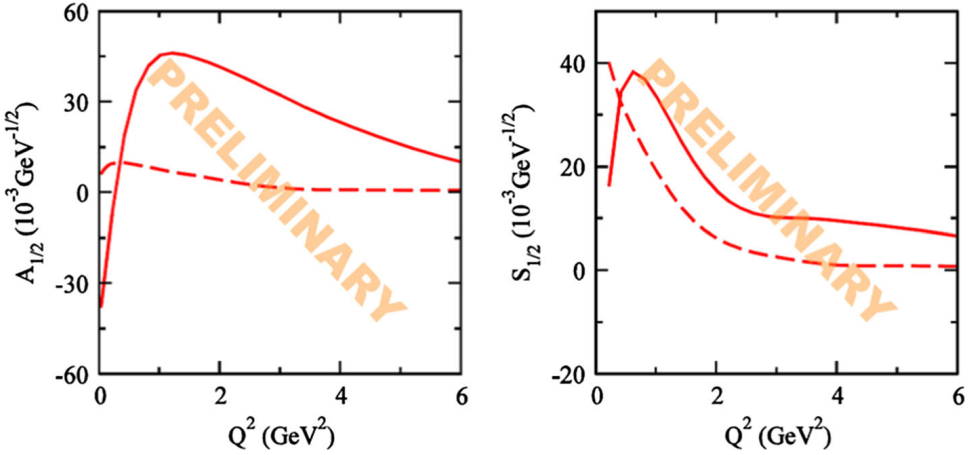




PRC75,015205(2007)(EM), PRC67,65201 (2003)(CC)

Example of transition form factors $N^*(1/2, 1/2^+)$

- 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)

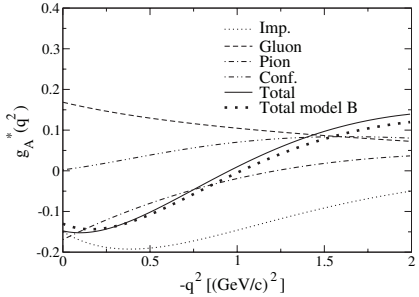


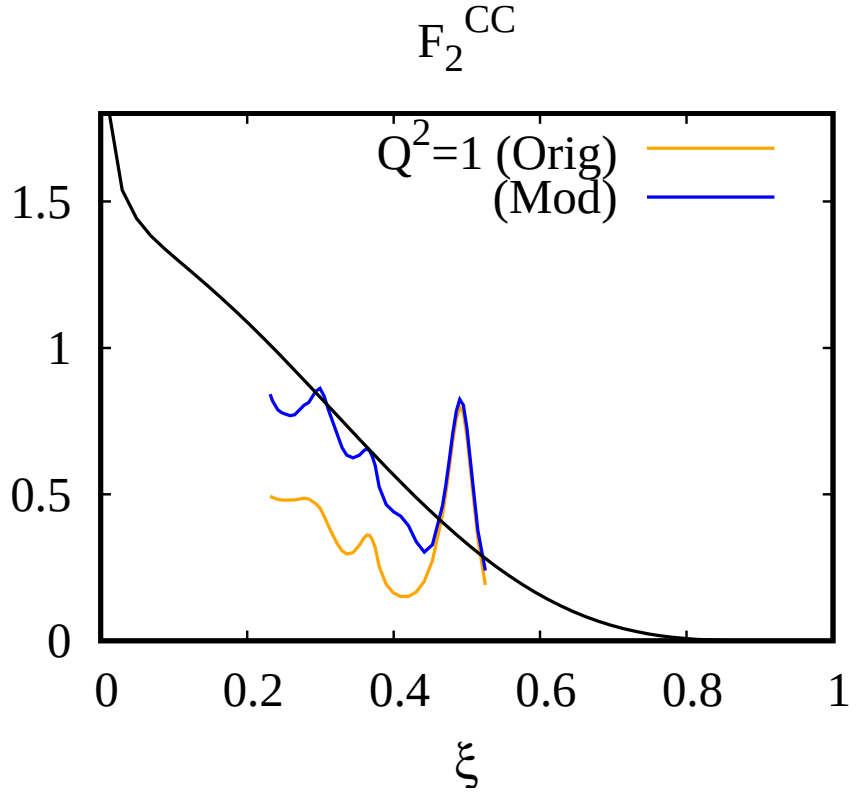
FIG. 7. Axial form factor $g_A^*(q^2)$. Notation as in the upper panel of Fig. 3.

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

Simple Exercise of DCC model

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

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



preliminary

ANL-Osaka DCC model

- 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

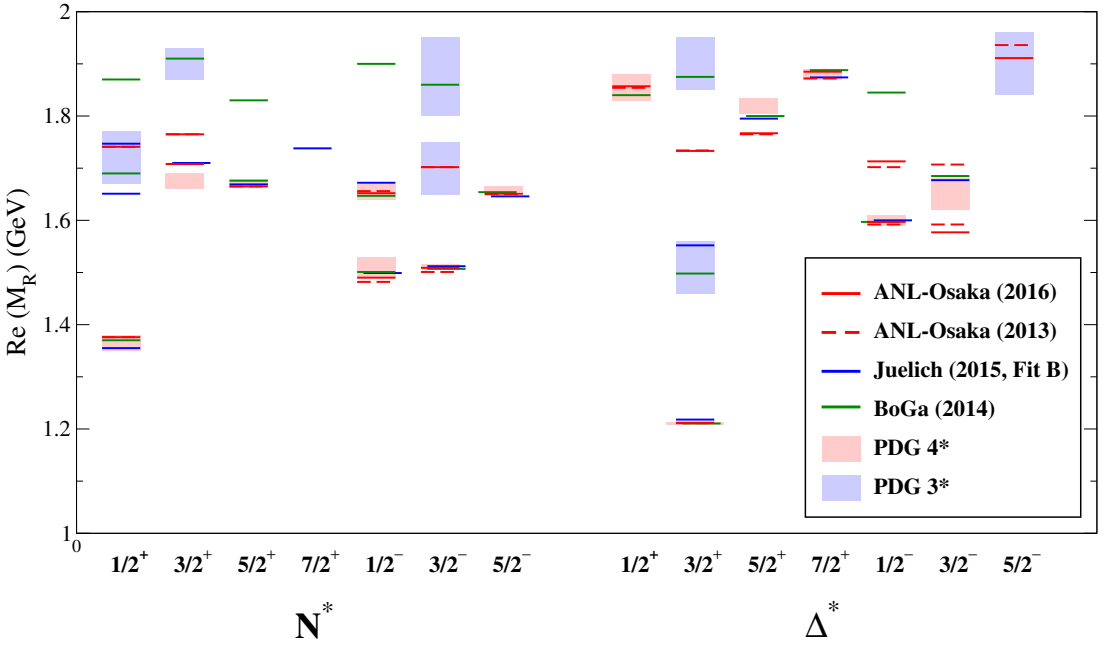
- ANL-OSAKA DCC model is extended to describe weak meson production reaction up to $W < 2GeV$.
- Neutrino induced single pon production in N^*, Δ resonance region is studied using ANL-Osaka model.
  Comparison with Neutrino event generators(NEUT, GENIE,NuWro,..) and other models will be very useful.
- 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.

Backup

Resonance properties from ANL-Osaka DCC model

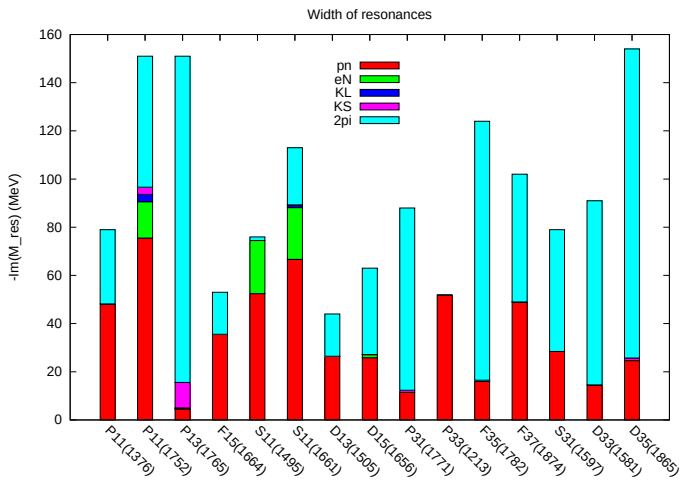
- N^* and Δ resonances

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



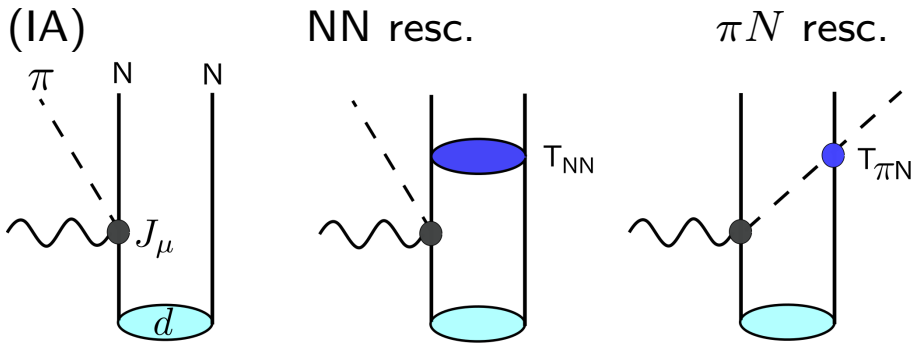
- Opening of meson-baryon channels: $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$..

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



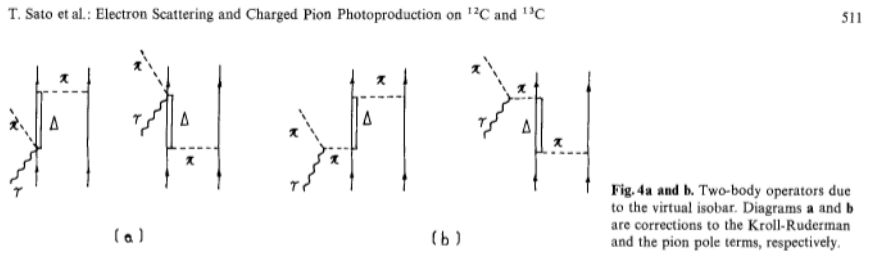
FSI and νd

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



note:

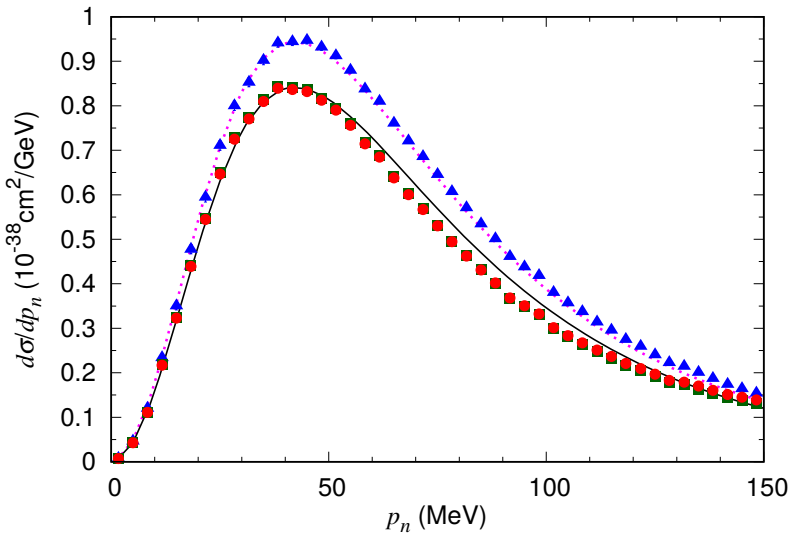
- Above rescattering terms are the leading order of multiple scattering theory(Faddeev Eq.). More elaborate description of three-body(πNN) dynamics may be possible(A. Matsuyama T.-S.H.Lee PRC34(1986), M. Schwamb Phys. Rep. 485(2010))
- 'Meson exchange current' is not considered.



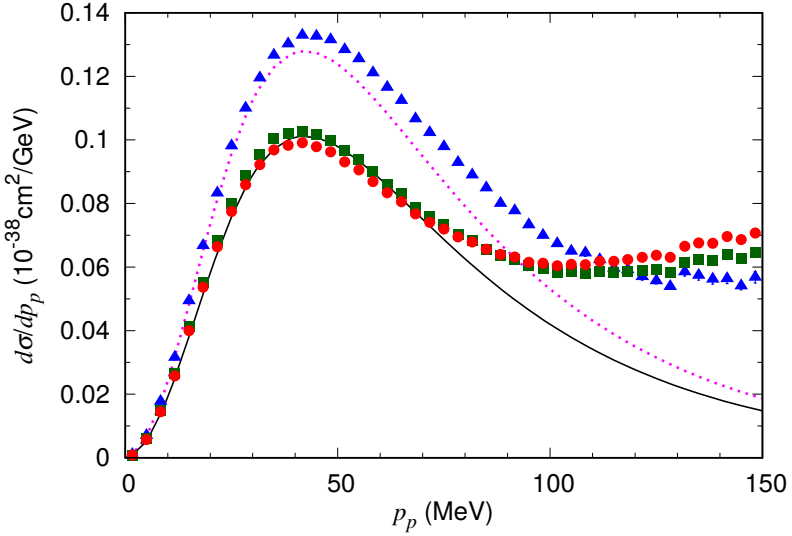
TS,K.Koshigiri, H. Ohtsubo,Z.Phys.A320(1985)

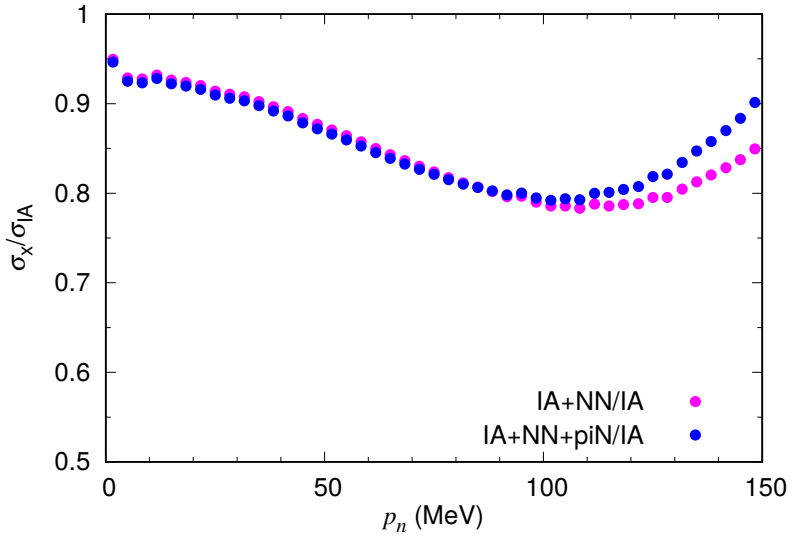
Effects of FSI $\nu_\mu + d \to \mu^- + \pi^+ + p + n$ $(E_\nu = 0.5GeV)$

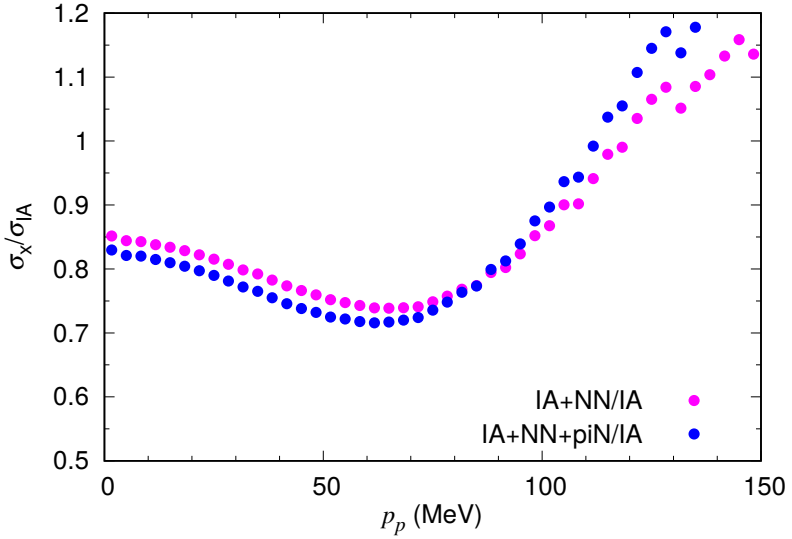
neutron spectator



proton spectator

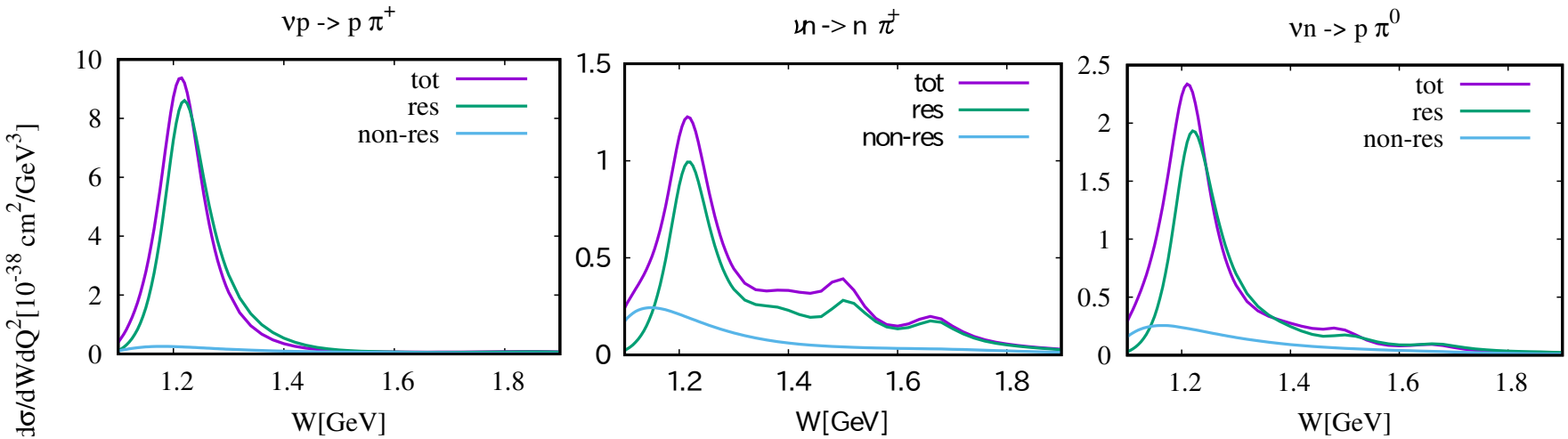






Res-NonRes single pion production(preliminary)

$$d\sigma/dWdQ^2 \quad \text{at} \quad Q^2 = 0.1GeV^2$$



- Integrating pion angle:
  $I = 3/2, I = 1/2$ amplitudes interfere, J^π diagonal,
- Angular distribution is more sensitive to non-res