Neutrino Induced Meson Production Reaction on Nucleon and Deuteron

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this talk:

I Dynamical model for Neutrino-nucleon interaction in the resonance region

S.X. Nakamura, H. Kamano, TS, PRD92 074024(15)

II Role of FSI in Neutrino-deuteron reaction

J.J. Wu, TS, T.-S. H. Lee PRC91 035203 (15)

Collaborators

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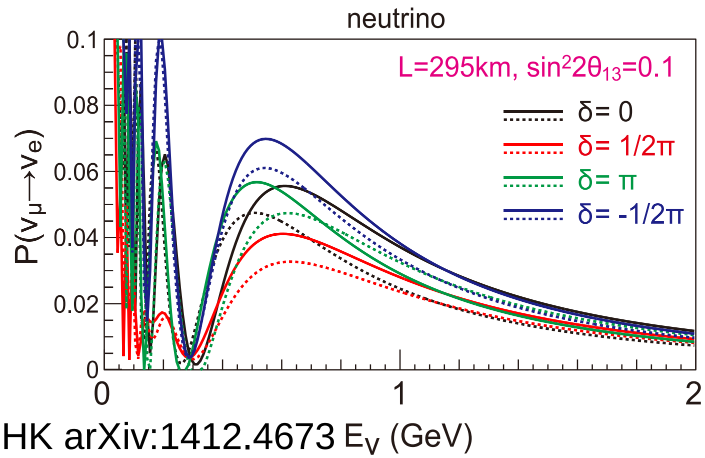
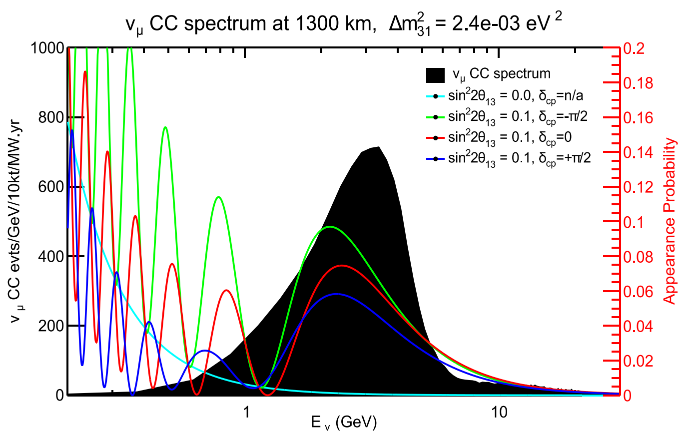


HK arXiv:1412.4673



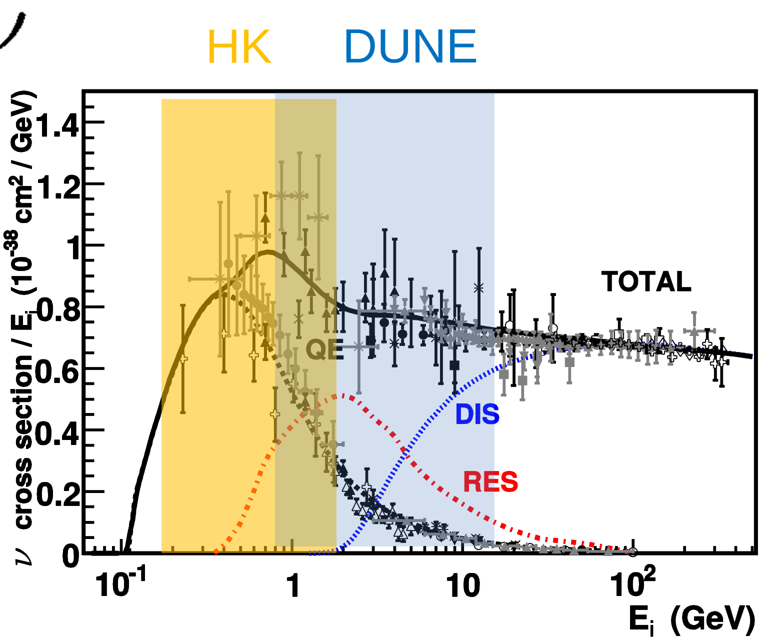
LBNE arXiv:1307.7335

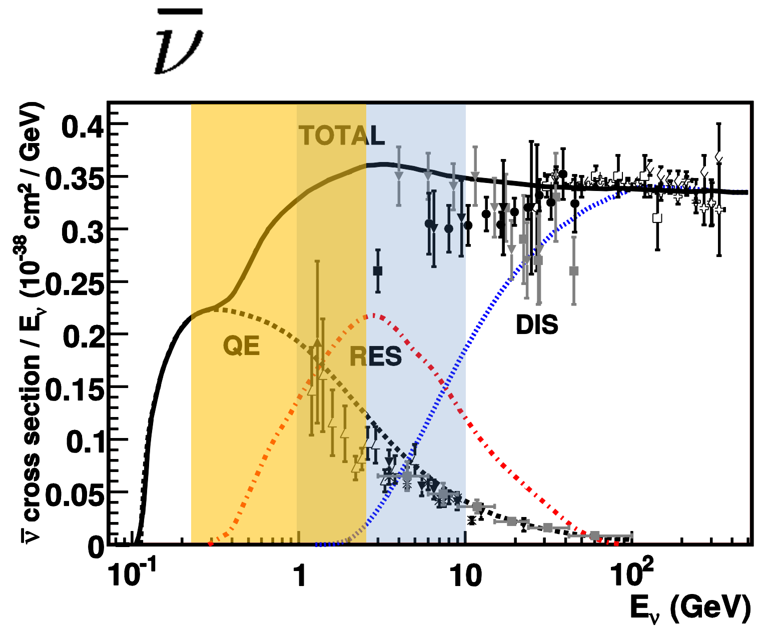
- CP violation in lepton sector
- Mass hierarchy
- Precise value of mixing angle
- Majorana or Dirac
- Absolute mass of neutrinos
- Sterile neutrinos

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

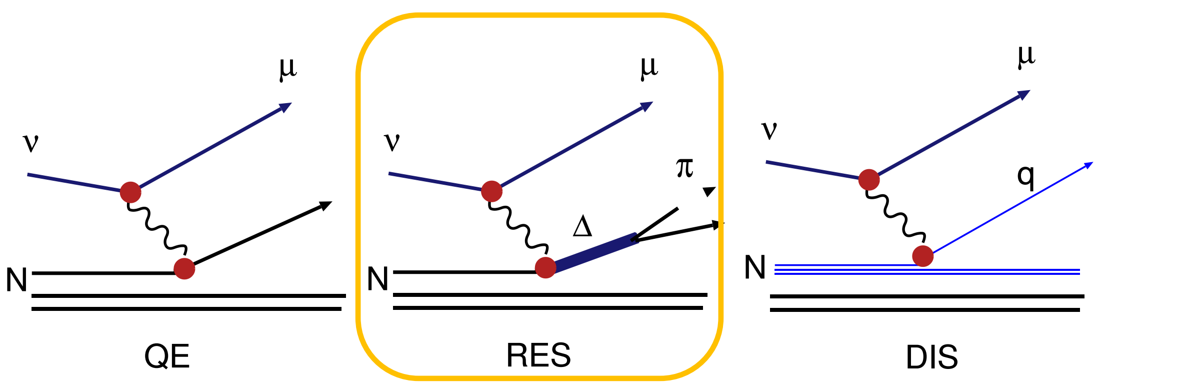
Precise understanding of neutrino nucleus-reaction for wide energy range is crucial to reconstruct neutrino-flux and extract neutrino properties.

Reaction Mechanisms of Neutrino-A





J.A.Formaggio G.P.Zeller RMP84(2012)



RES is important mechanism in GeV neutrino reaction

I Dynamical model for Neutrino-nucleon interaction in the resonance region

ν-Nucleon interaction as a input to study ν-Nucleus reaction
description from $\Delta_{33}(1232)$ up to W < 2GeV (DIS: W>2GeV, $Q^2 > 1\sim2\mathrm{GeV}^2$)

Isobar models

: Rein-Sehgal(ann. Phys 133), Alvarez-Ruso et al.(prc57), Paschos et al.(prd65),
Lalakulich et al.(prd71), Hernandez et al.(prd76) and recent references.

rcompact formula, useful for neutrino-reaction event Generators(NEUT,GENIE,NuWro..)
and for reaction models(GiBUU)

Dynamical coupled channel(DCC) reaction model

Meson-baryon channels $\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \ldots$, connected through unitarity

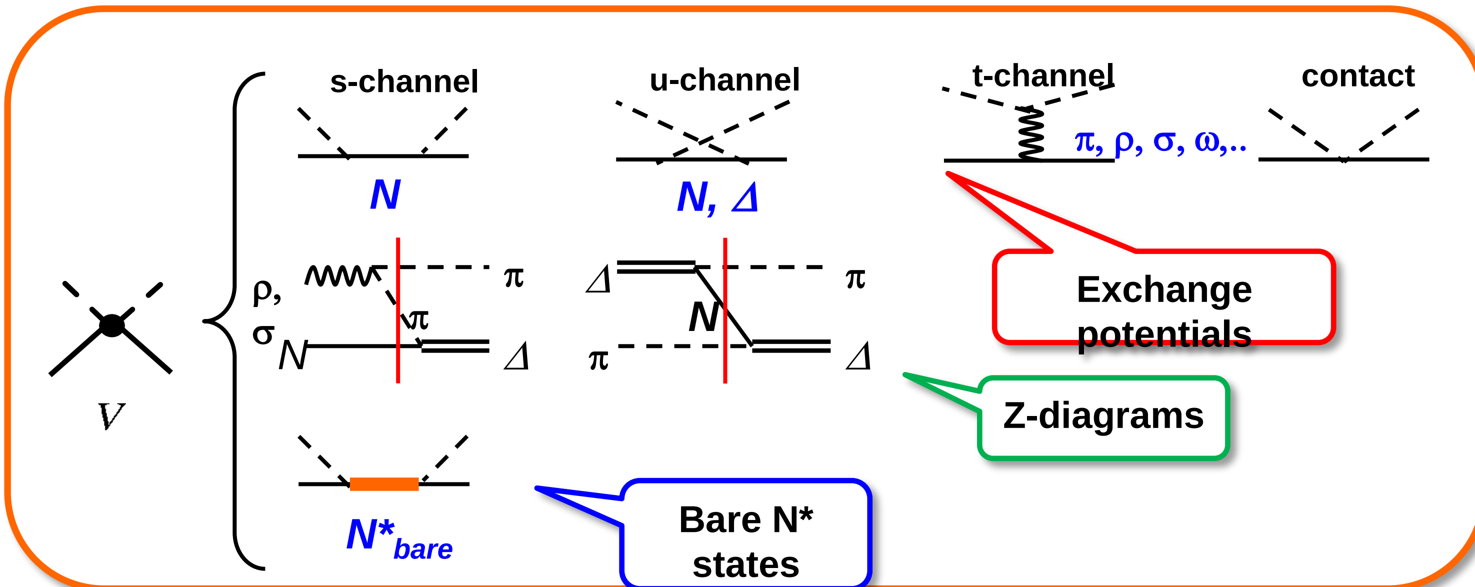
DCC model is developed by the simultaneous analysis of pion, photon induced reactions, to investigate N*,Delta properties(spectrum of nucleon resonances, form factors, branching ratio)

Brief description of DCC model

Fock Space

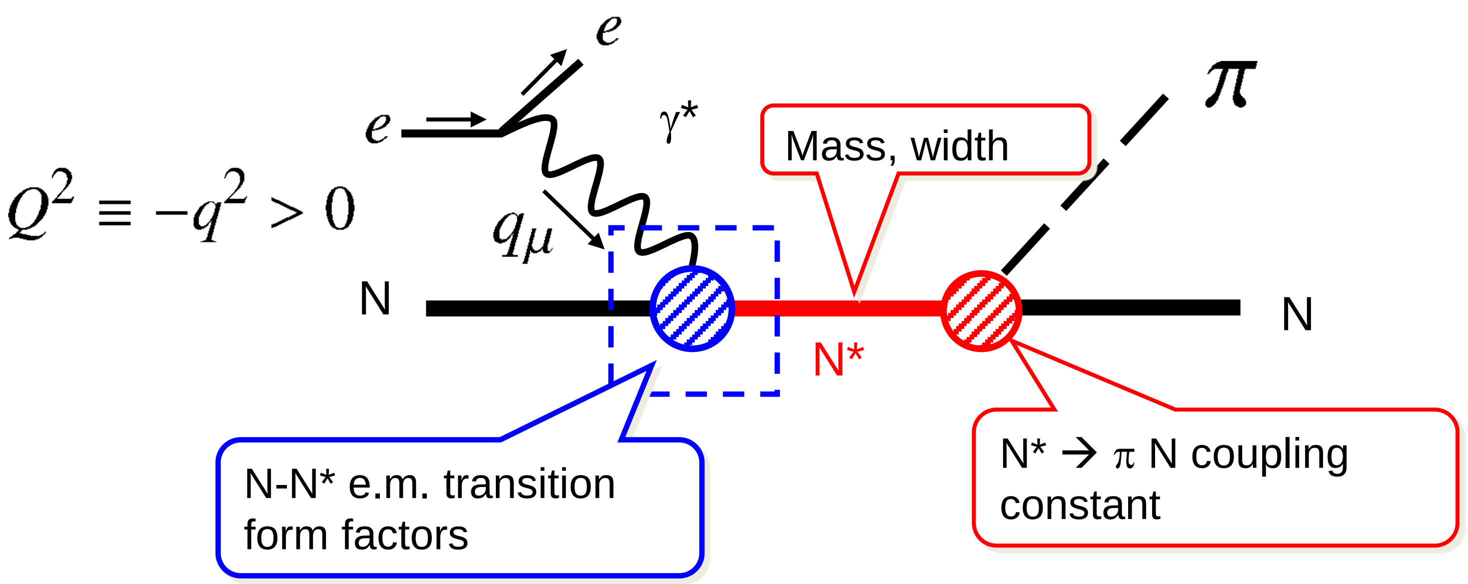
$$a, b, c \;=\; (\,\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\boxed{\pi\Delta,\ \sigma N,\ \rho N}}_{\pi\pi N}\ K\Lambda,\ K\Sigma, \cdots)$$

Interaction



Solve LS equation, three-body unitarity is respected.

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) \;=\; V^{(LSJ)}_{a,b}(p_a, p_b; E) + \underbrace{\sum_c}_{\text{coupled-channels effect}} \int_0^\infty q^2 dq V^{(LSJ)}_{a,c}(p_a, q; E) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$



Analysis of pion, photon induced reactions within DCC model (PRC88 035209 (13))

objective of the analysis is to find properties of nucleon resonances.

23,000 data points (differential cross section, polarization, ..)

Extension of the model for neutrino reaction

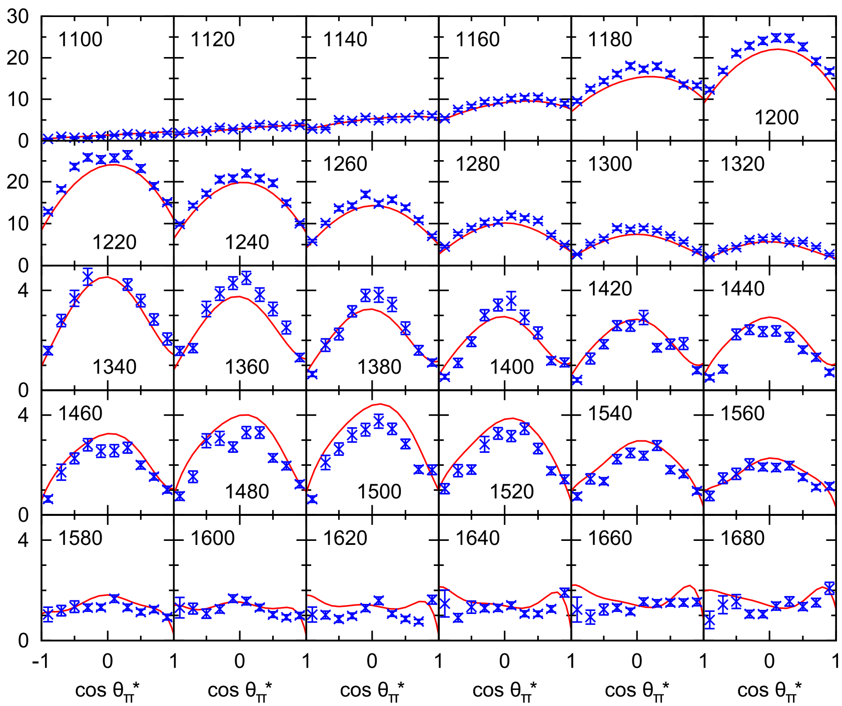
- Vector current: isospin-decomposition for CC,NC (neutron PRC94 015201(16))
  finite Q2 (electron scattering data)

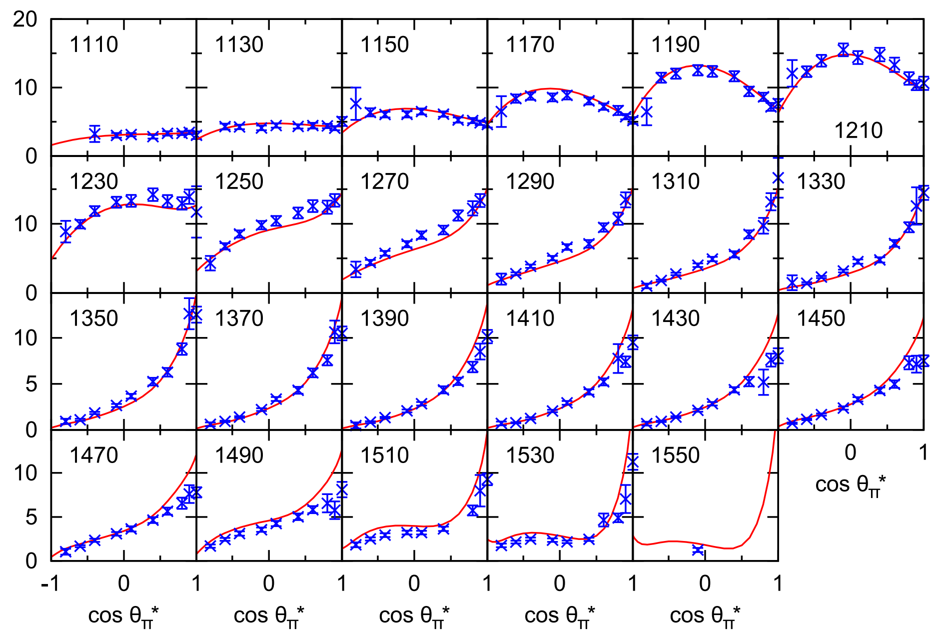
- Axial vector coupling constant: PCAC $g_{\pi NN^*} \to g_{ANN^*}$

DCC model: eN reaction I single pion production

W-dependence of pion angular distributions at Q^2=0.4GeV^2

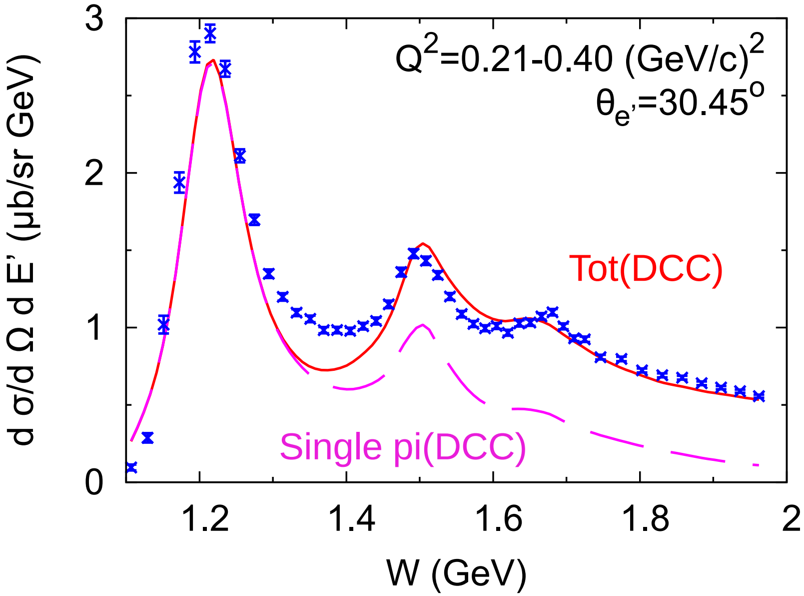
$$p(e,e'\pi^0)p \qquad \frac{d\sigma_T}{d\Omega}+\epsilon\frac{d\sigma_L}{d\Omega} \qquad p(e,e'\pi^+)n$$

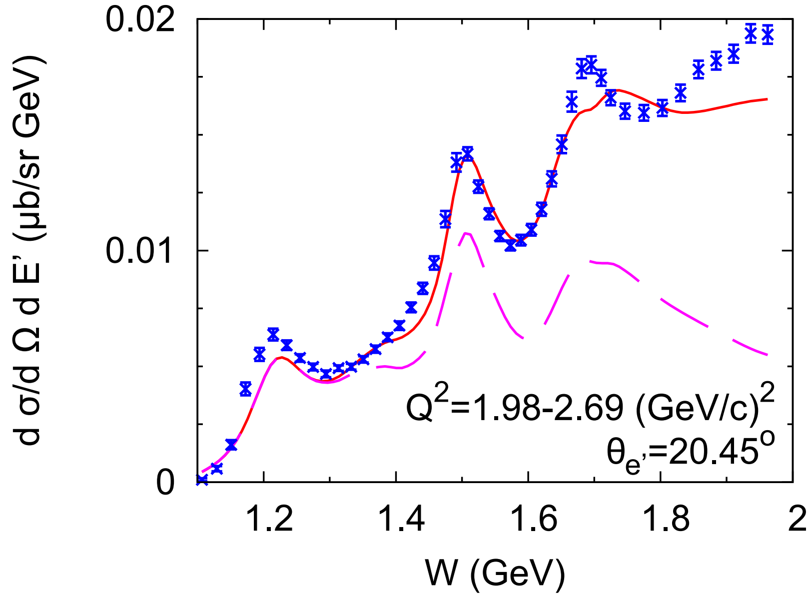




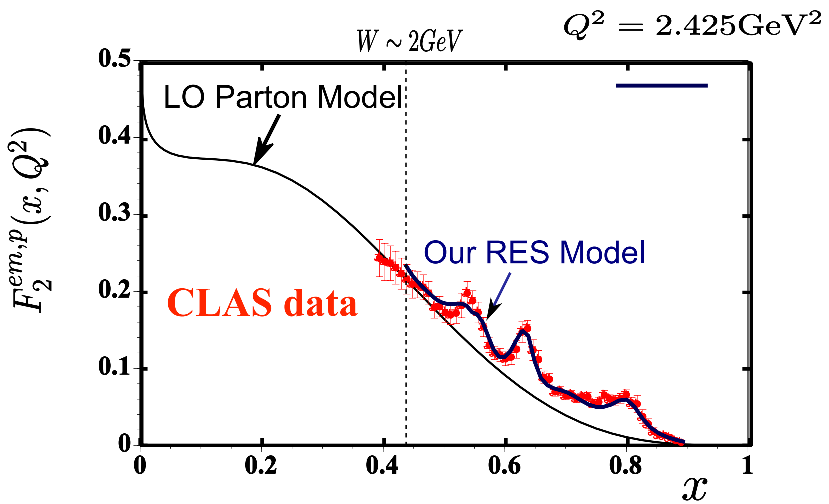
Comparison with CLAS data

DCC model: eN reaction II inclusive cross section





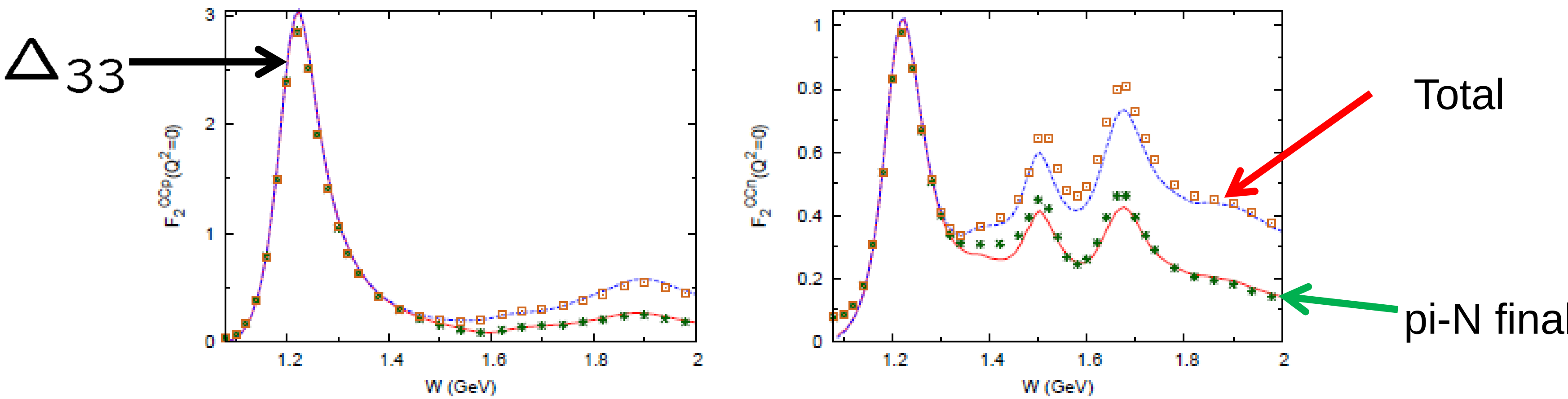
Resonance(W< 2GeV) to DIS(W>2GeV, Q^2 > 2GeV^2)



DCC model: nuN reaction I inclusive cross section

W-dependence of structure function at Q^2=0

Proton Neutron

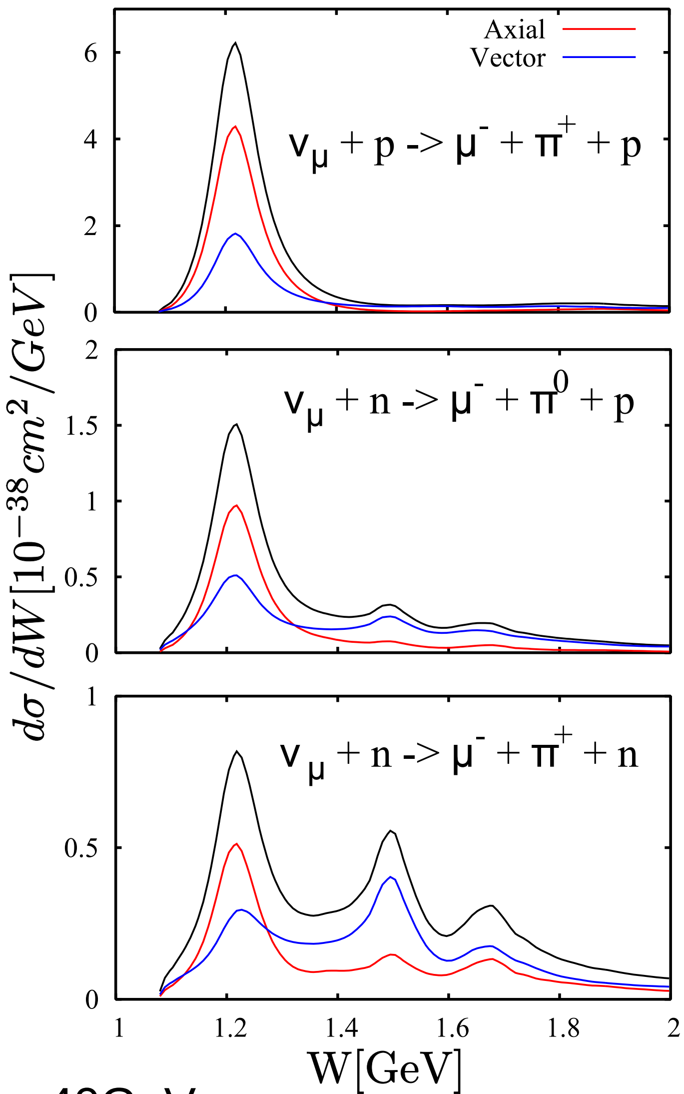


Charge current neutrino reaction

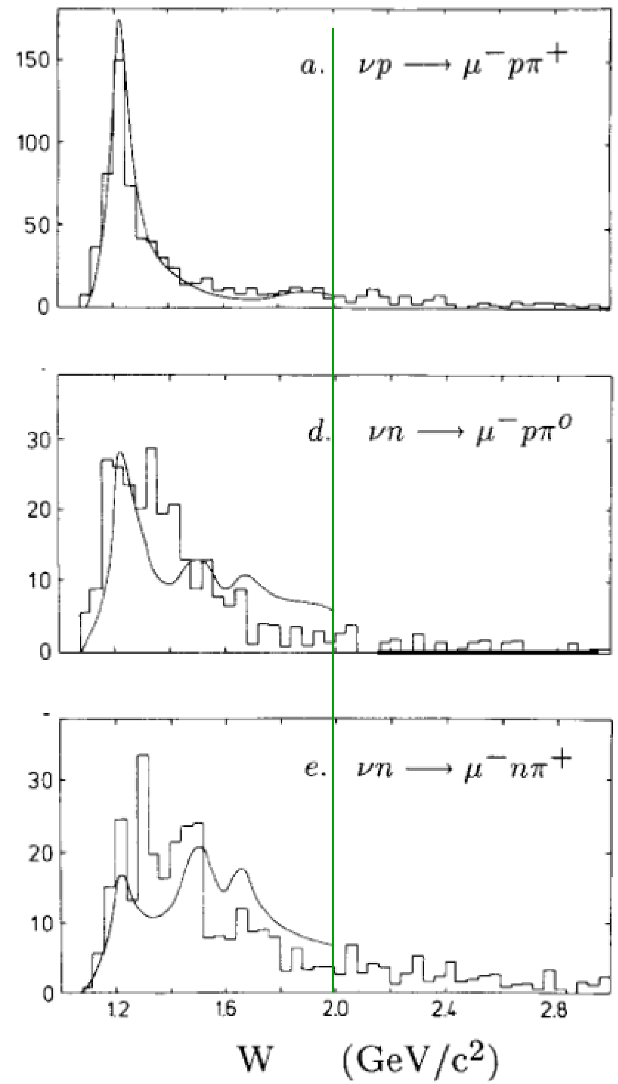
proton : Δ_{33} dominance

neutron : W>1.3GeV non-resonant and other resonance start to contribute, appreciable contribution of two pion production.

DCC model: nuN reaction II single pion production

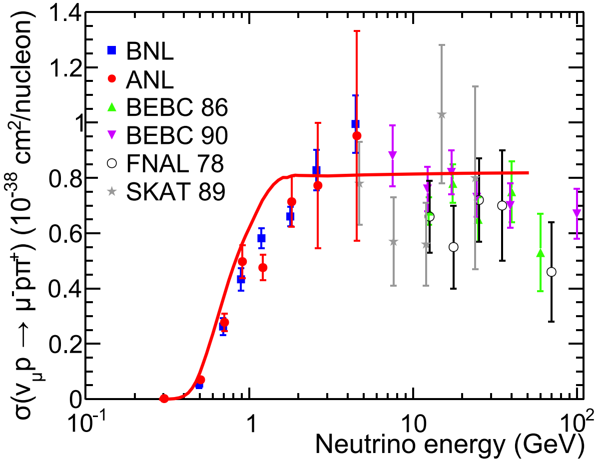


E_nu=40GeV



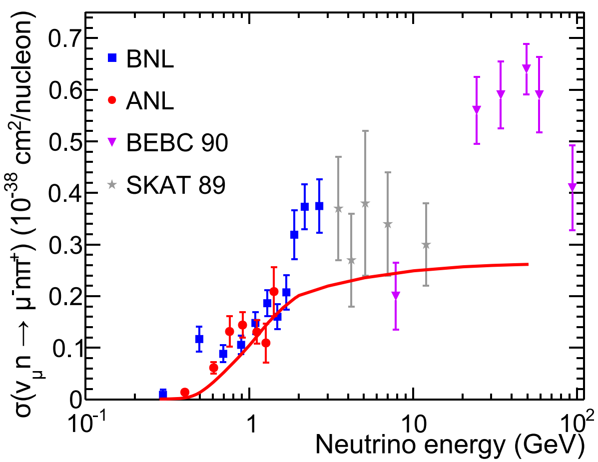
BEBC NP343, 285(1990)

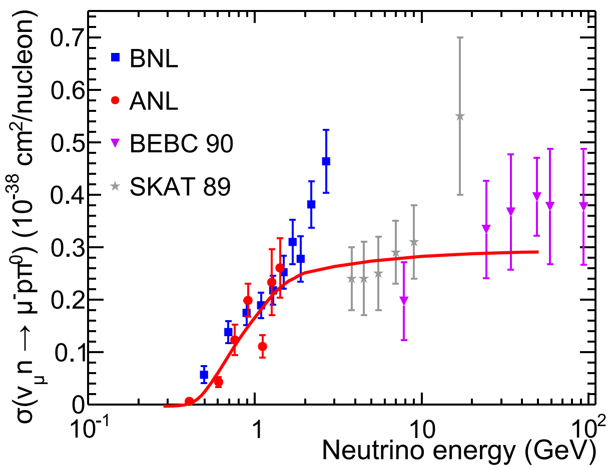
DCC model: nuN reaction III single pion production



Axial vector coupling of Delta(1232), non-resonant mechanism can be studied from 'data'
E_nu < 2GeV and W cut ~1.4GeV

DCC model





Figs of data from P. Rodrigues et al, arXiv:1601.01888

II Role of FSI in Neutrino-deuteron reaction

Compilation of Low energy ($E < 30 GeV$) Neutrino Cross Section
(http://hepdata.cedar.ac.uk/review/neutrino/)

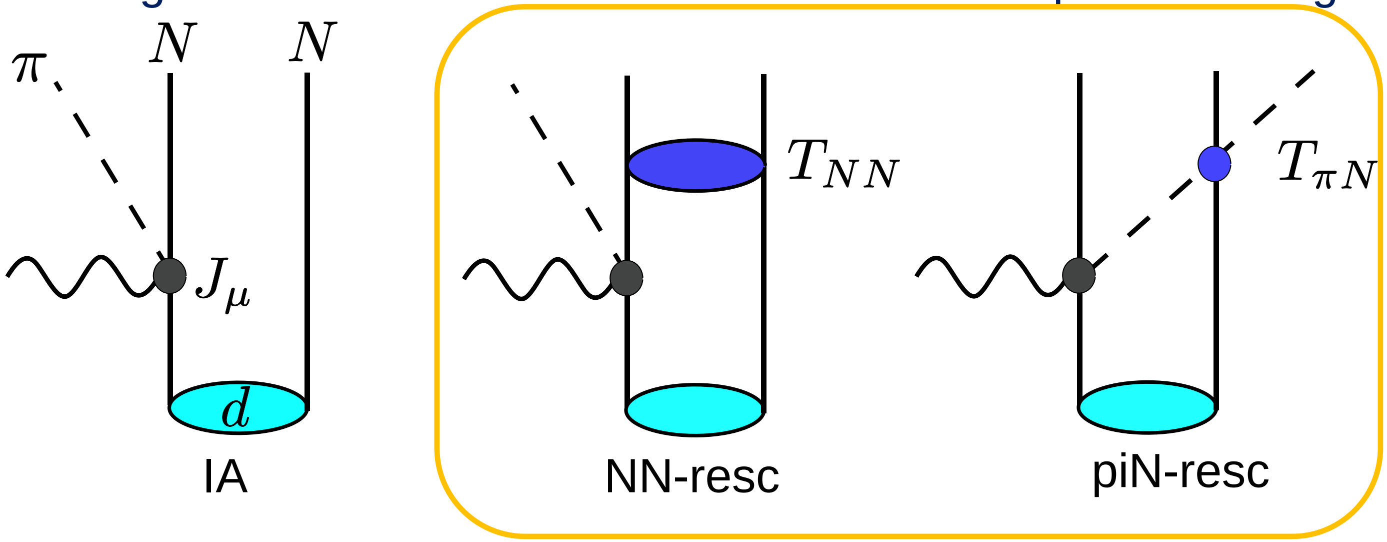
				1π	2π
GGM	Lerche 1978	ν	Propane	1-10	
	Bolognese 1979	$\bar{\nu}$	Propane-Freon	1-7.5	
BEBC	Allen 1986	ν	p	10-80	
	Allasia 1990	$\nu, \bar{\nu}$	d	5-150	
BNL	Kitagaki 1986	ν	d	0.5 - 3	0.5 - 3
ANL	Barish 1979	ν	p,d	0.4 - 6	
	Radecky 1982	ν	d	0.5 - 1.5	
	Day 1983	ν	d		0.75-5.55
FNAL	Bell 1978	ν	p	15-40	
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), Rodrigues et al. arXiv:1601.01888)

Nuclear effects

initial state: Fermi-averaging
final state : rescattering in final state
many-body pion production, pion absorption

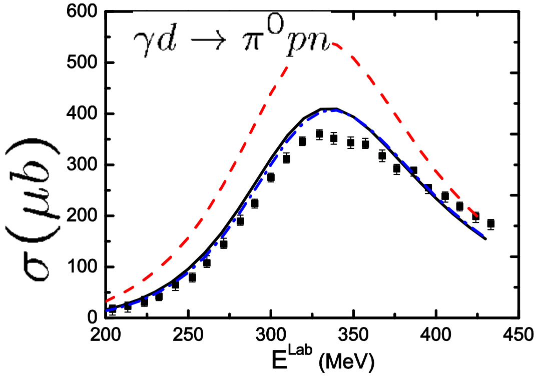
Rescattering effects within the first order terms of multiple scattering theory

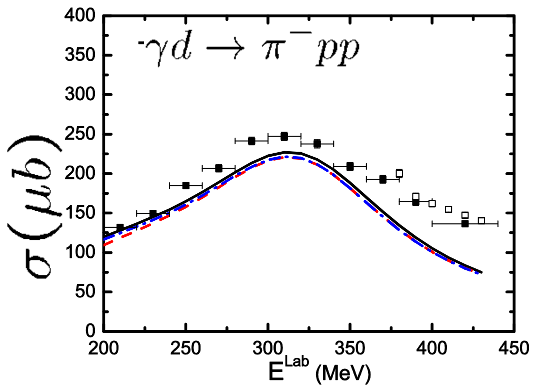


Impulse + NN rescattering = Distorted wave NN wave function

$$
\begin{aligned}
|\psi^+(DW)> &= |\phi_0(PLW)> + G_0^+(E)V|\psi^+(DW)> \\
&= (1 + G_0^+(E)T(E))|\phi_0(PLW)>
\end{aligned}
$$

Total cross section(gamma-d)





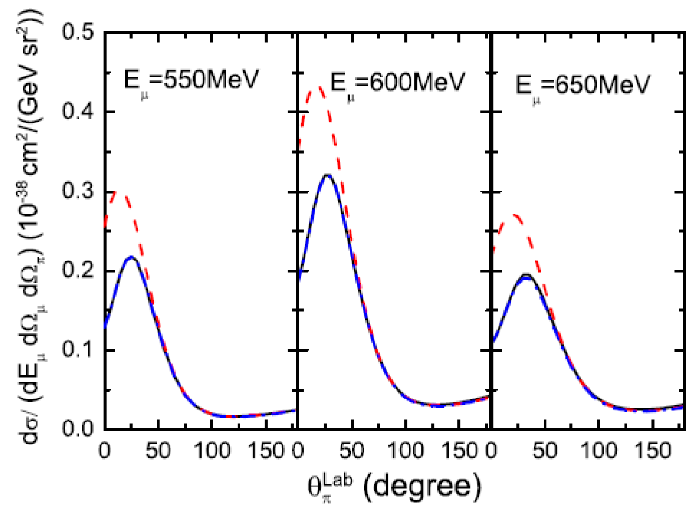
Impulse

Impulse + NN

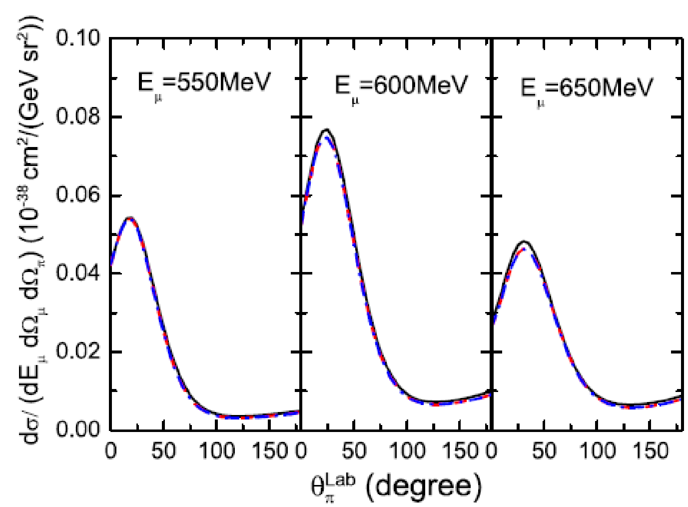
Impulse+NN+piN

Nu-d (E_nu=1GeV, theta_mu=25deg)

$$\nu_\mu d \to \mu^- \pi^+ pn$$



$$\nu_\mu d \to \mu^- \pi^0 pp$$



Summary

Model of weak meson production reactions including two-pion production channel for W<2GeV, $Q^2<3\ GeV^2$ is developed

- vector current is obtained from the analysis of electron and photon induced reactions.
- axial vector current is constructed using PCAC (Dipole form factor is assumed)
- The model smoothly connects DIS and RES(em) regions

Rescattering effects are examined for electroweak deuteron reactions

- Using, pion production model of SL and Bonn-Pot, pion(pi^-,pi^0) photoproduction on deuteron are reasonably well described.
- Neutrino induced pion production reaction(CC) (Within the kinematical region we have examined)

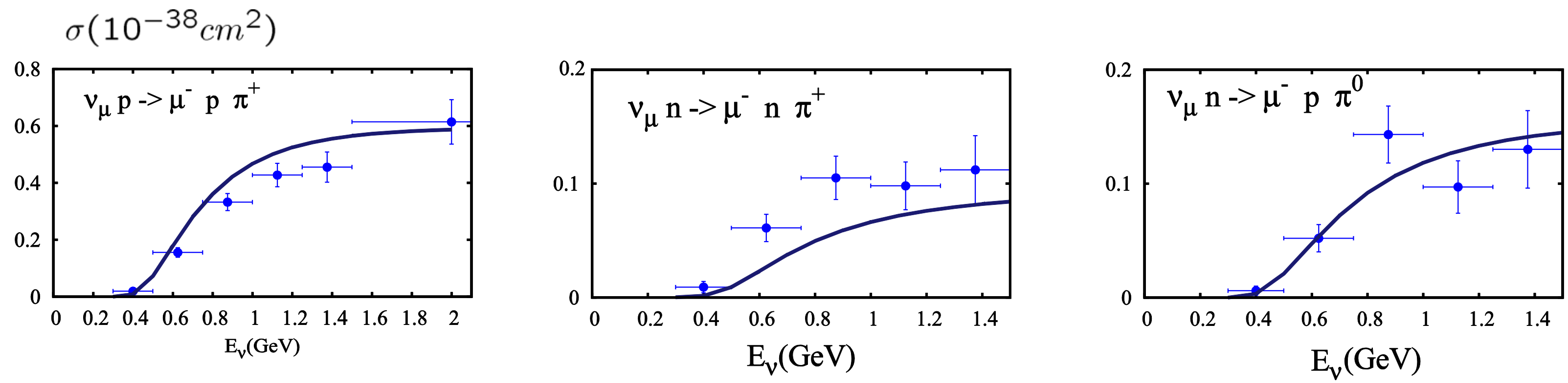
Large effects of nucleon rescattering even Delta-QE peak
especially FSI in $^3S_1$ $>$ $^1S_0$

Back up

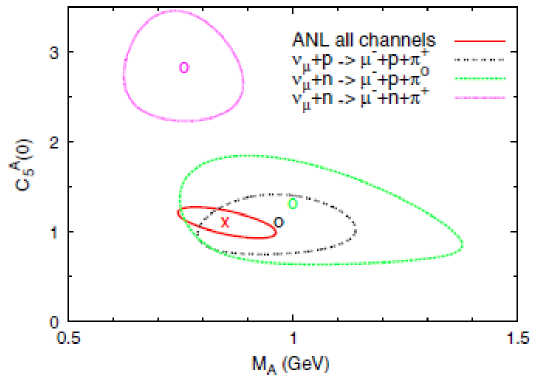
All three channels are not understood simultaneously

Model:
Sato,Uno,Lee PRC67(2003) CC
Matsui,Sato,Lee PRC72(2005) NC,PV(e,e')

Comparison with G. Radecky et al.(ANL)

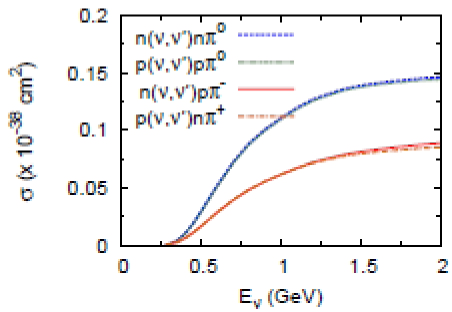


Similar observation by
K. Graczyk et al. prd90 093001(2014)
E. Hernandez et al. prd76 033007(2007)
But all are explained by
O. Lalakulich et al. prd82 093001 (2010)

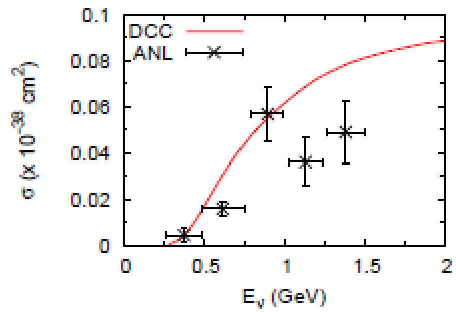


Comparison with the available data (other than CC 1pi)

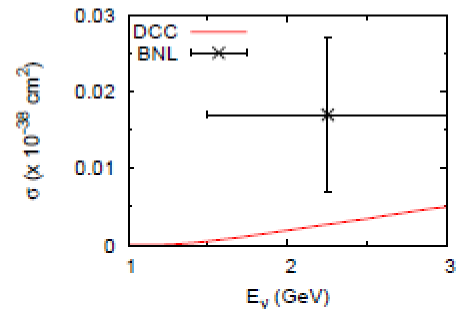
NC(single pion)



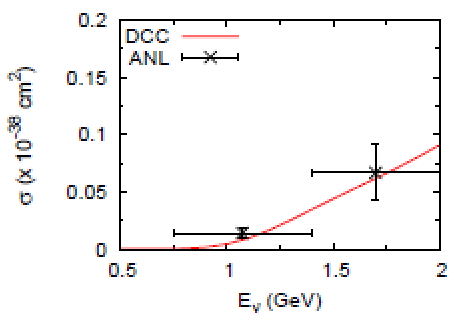
$\nu n \to \nu p \pi^0$



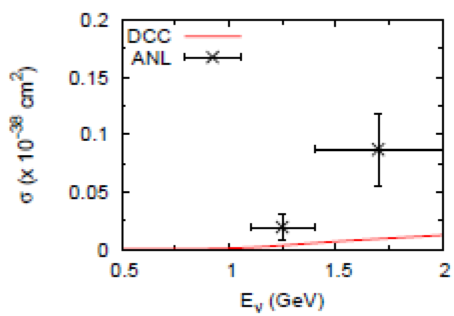
$\nu_\mu n \to \mu^- K^+ \Lambda$



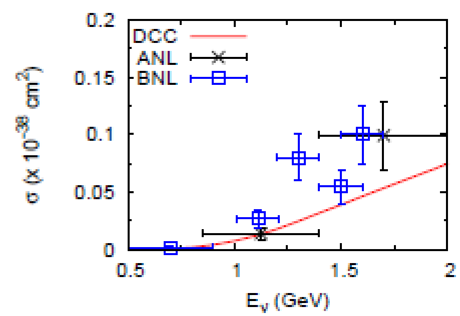
$\nu_\mu p \to \mu^- \pi^+ \pi^- p$



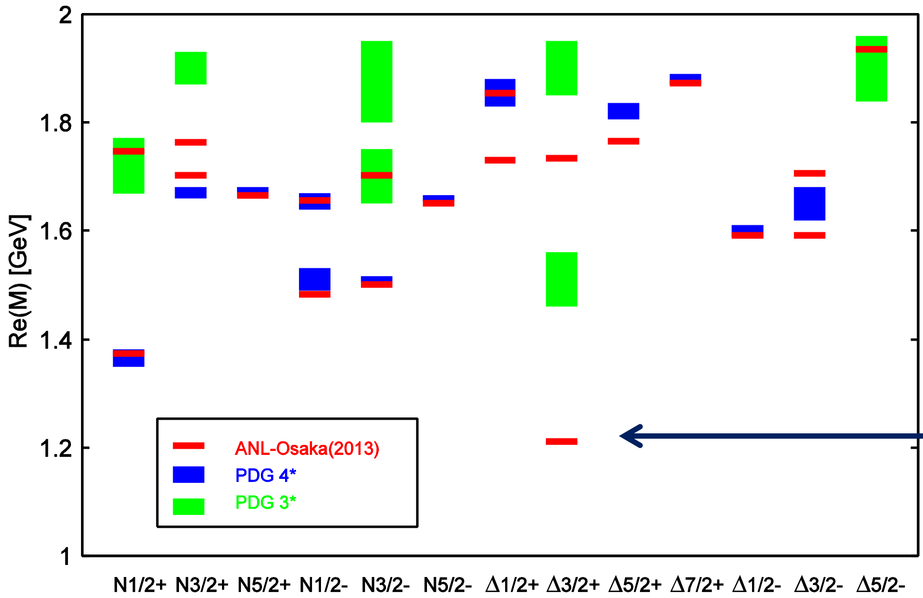
$\nu_\mu p \to \mu^- \pi^+ \pi^+ n$



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



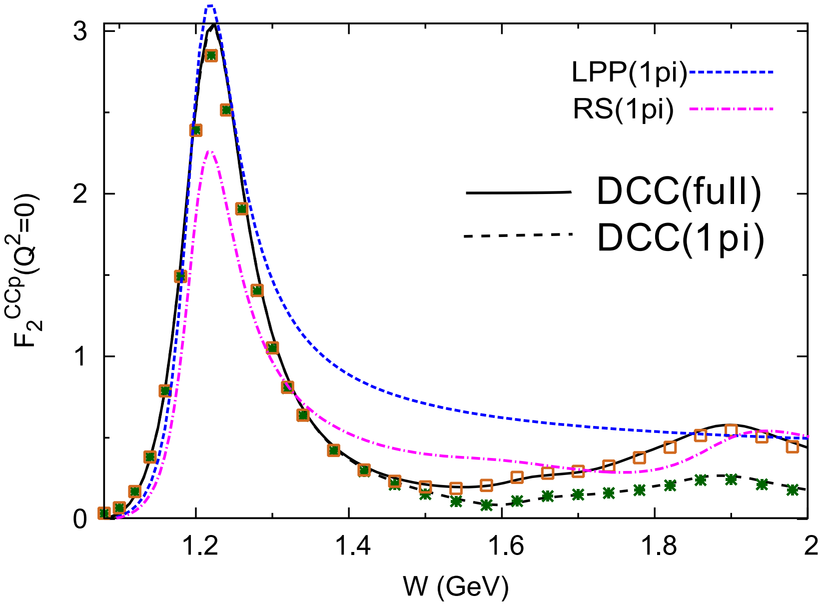
N* and Delta spectrum extracted from the pole of DCC partial wave amplitude

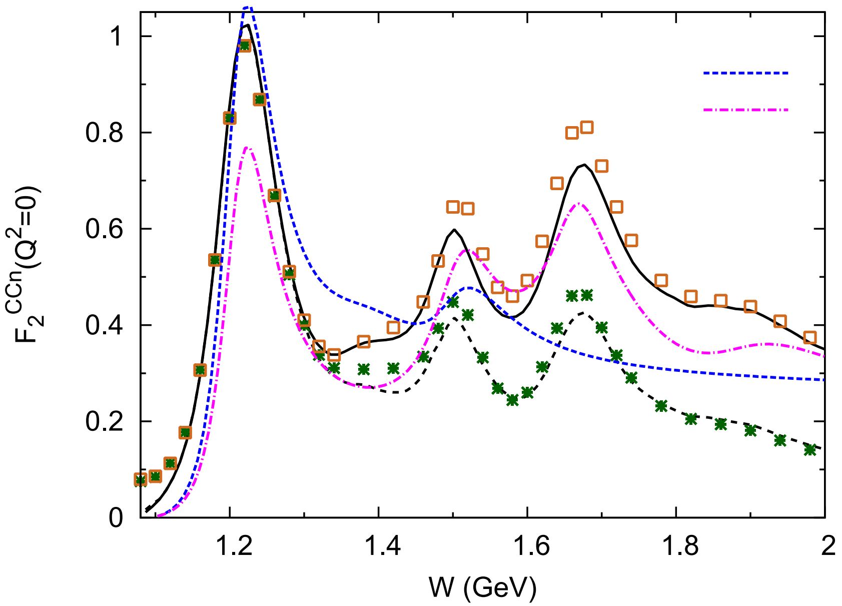


Spectrum of N*
and Delta (ANL-Osaka)

$\Delta_{33}(1232)$

Compare DCC with RS and LPP models



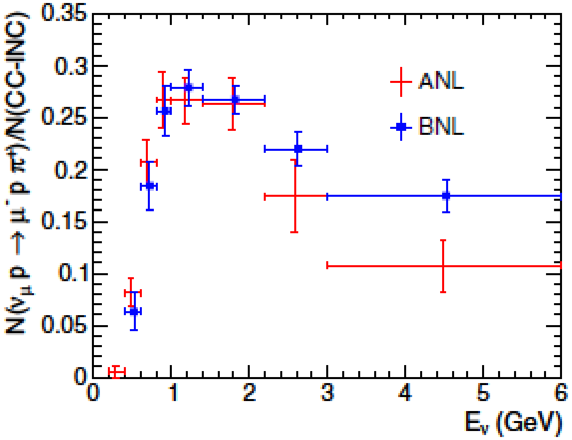


Possible solution of ANL/BNL data

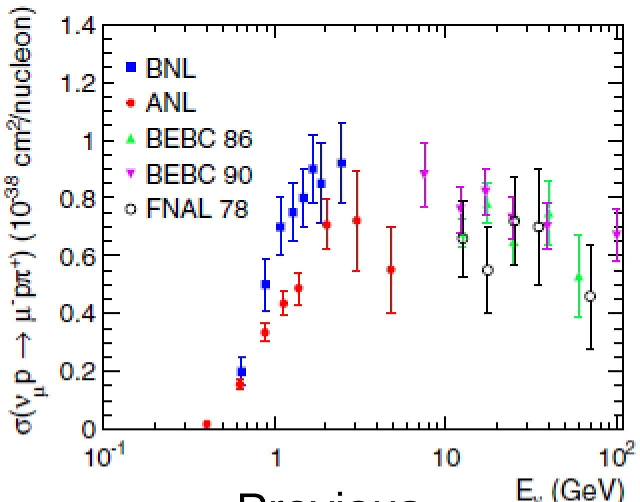
C. Wilkinson, P. Rodrigues, S. Cartwrite, L. Thompson, K. McFarland, PRD90, 112017 (2014)

Rate N is cross section times flux

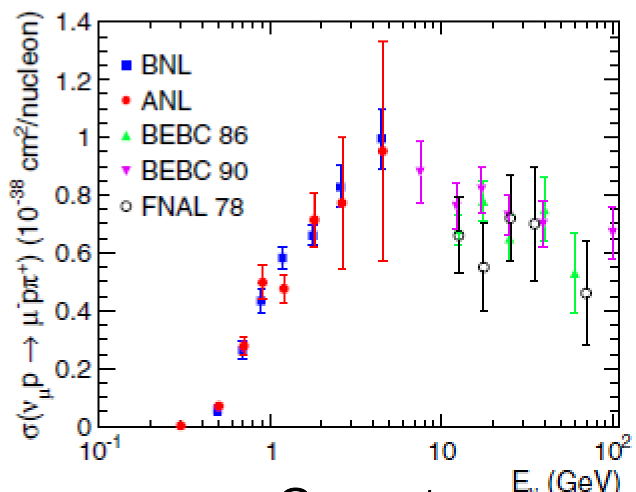
$$N_X(E) = \sigma_X(E)\Phi(E)$$



If one takes ratio of ppi+/CCQE
of each data(flux independent),
ANL-BNL data are consistent



Previous



Current