Neutrino Nucleon interaction in the few-GeV region

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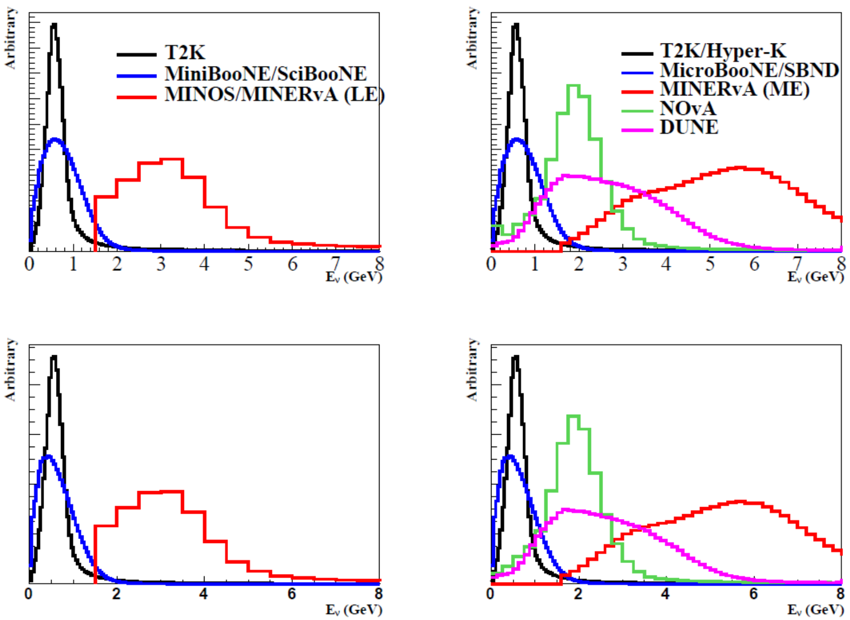
Review article arXiv:1610.01464

Jan. 2017 KEK-HN-2017, KEK

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

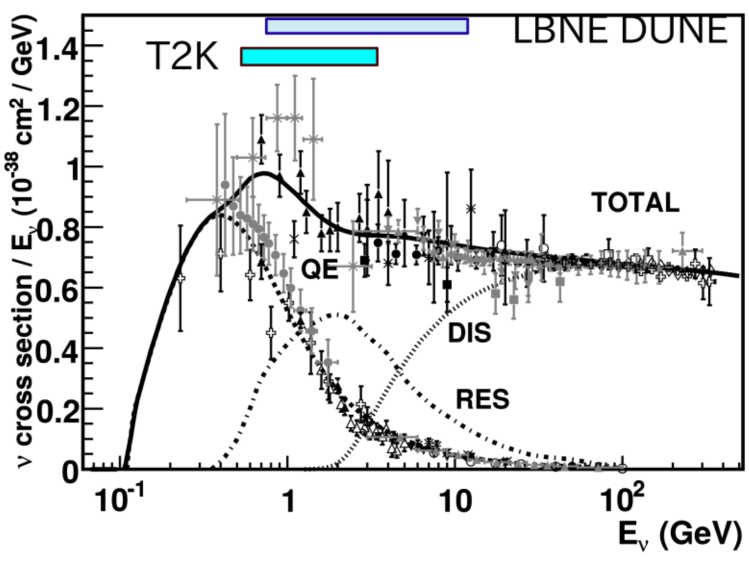
Neutrino flux prediction of current and future accelerator neutrino experiments



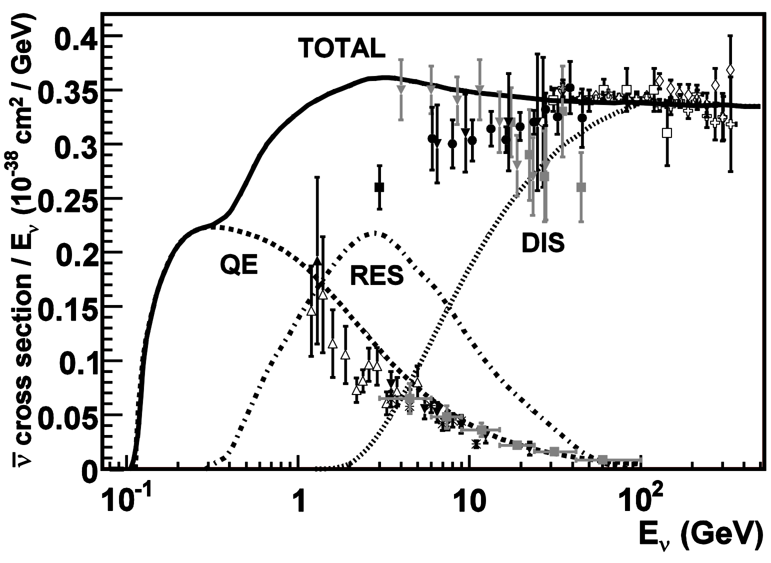
neutrino

anti-neutrino

T. Katori and M Martini arXiv 1611.07770 neutrino



Anti-neutirno

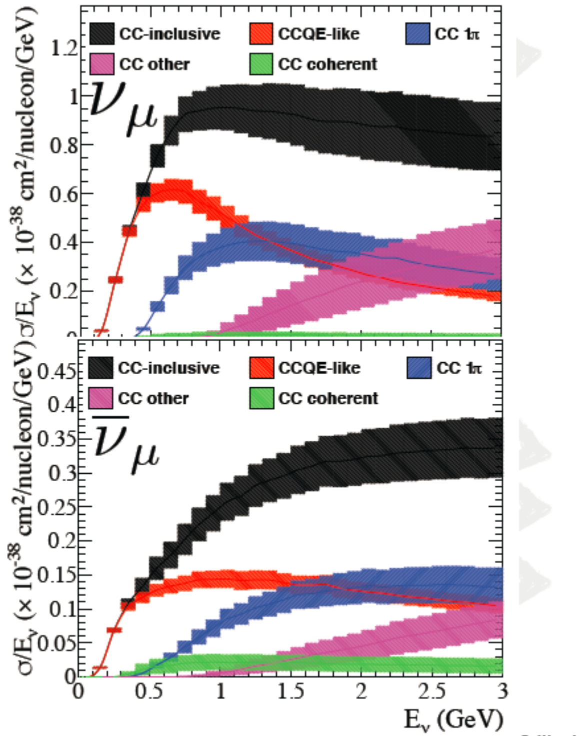


J. A. Formagglo and G. P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

NEUT interaction model

2014 model & parameters (NEUT v5.3.3)

- CCQE: Llewellyn Smith, M_A^{QE}=1.0 GeV/c^2
- CC resonant π: Rein-Sehgal, M_A^{RES}=1.2 GeV/c^2
- 2p2h: Nieves model
- Nuclear model: Smith-Moniz RFG
    - Also have 2D spectral function implemented
- RPA effects included
- Coherent pion: Rein-Sehgal
- DIS with Bodek-Yang corrections
- Neutrino and antineutrino interactions simulated
- ν_μ and ν_e simulated
    - Only differ at low energy
    - Radiative corrections
- Second class currents



T2K

Neutrino Frontiers, 2016 11 29

Morgan O. Wascko
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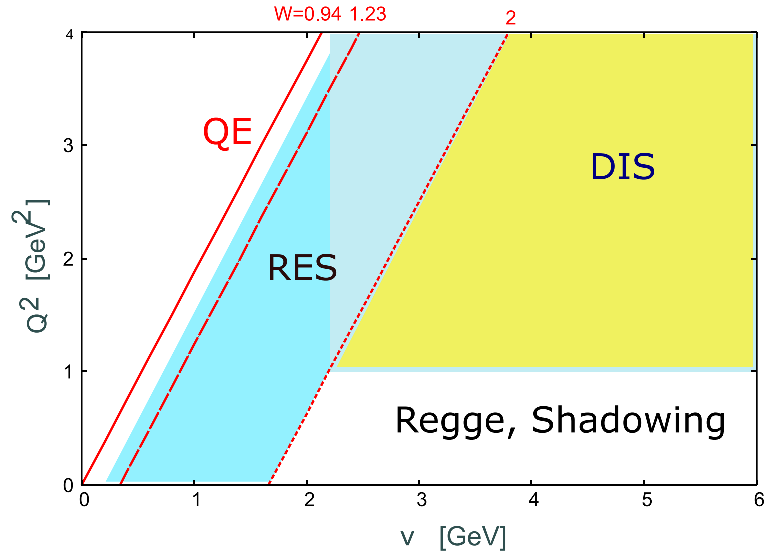
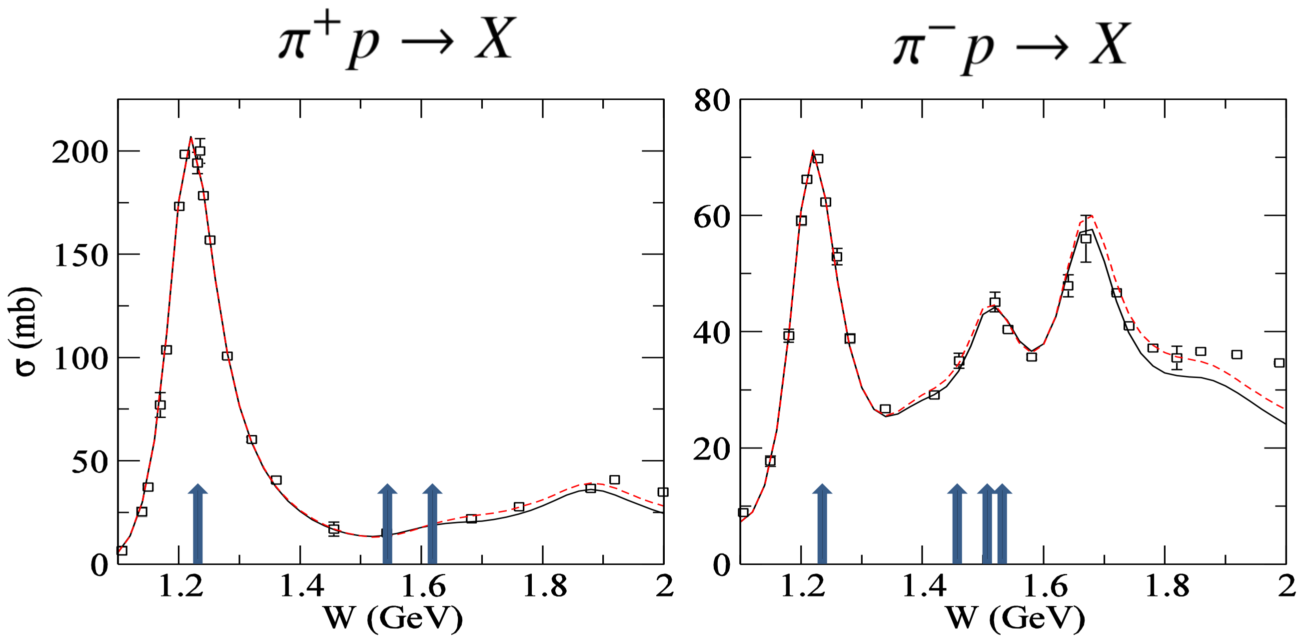
M. O. Wascko, Neutrino Frontiers, 2016 11 29

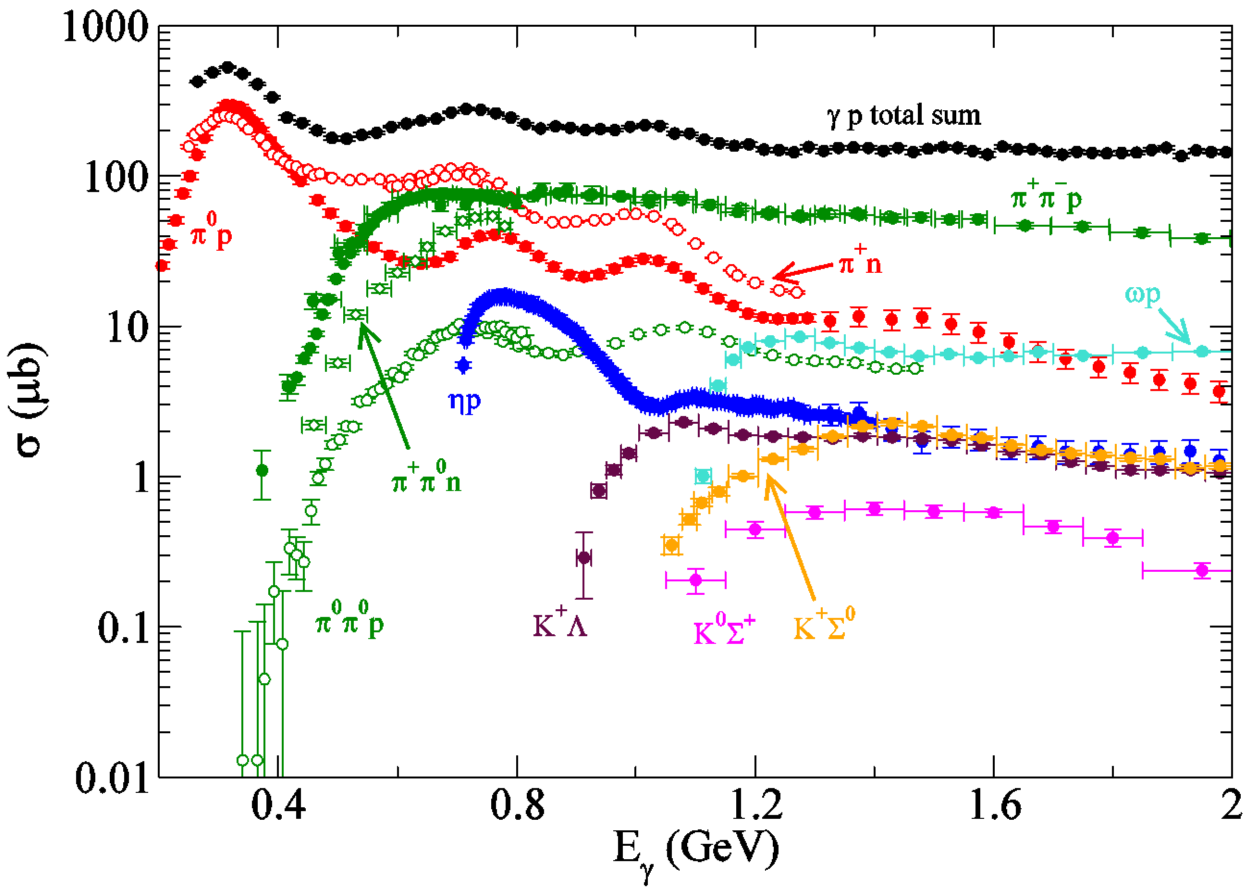


- Nucleon
- Resonance $W < 2GeV$
- DIS $W > 2GeV, Q^2 > 1GeV^2$
- $W > 2GeV, Q^2 < 1GeV^2$

Feature of N*,Δ resonances

- excite states of nucleons are unstable particles and appear as resonances
- strong coupling of excited states with meson-baryon continuum
  large width (~> 100MeV) and overlapping resonances





1000
100
10
1
0.1
0.01
σ (μb)
0.4
0.8
1.2
1.6
2
E$_\gamma$ (GeV)
γ p total sum
$\pi^+\pi^-$p
π^0p
π^+n
ωp
ηp
$\pi^+\pi^0$n
$\pi^0\pi^0$p
$K^+\Lambda$
$K^0\Sigma^+$
$K^+\Sigma^0$

amplitudes of MB production(J+ N -> M + B) are related through unitarity

$$Im(T)_{MB,JN} = \sum_{n=M'B',\pi\pi N} T^{\dagger}_{MB,n} T_{n,JN}$$

Need for the coupled channel analysis of various Meson-Baryon channel
to disentangle nucleon resonances

Below two-pion production threshold

phase of electroweak pion production amplitudes (Watson theorem)

$$T^{\alpha}_{\pi N,JN} = e^{i\delta^{\pi N}_{\alpha}} |T^{\alpha}_{\pi N,JN}|$$

Role of phase of amplitudes for $d\sigma/d\Omega, \Sigma, E, \ldots$

Reaction model of neutrino induced meson production reaction

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

$$J^{\rm CC}_{\mu}(x) = V_{ud}(V^{\pm}_{\mu}(x) - A^{\pm}_{\mu}(x)) \ ,$$
$$J^{\rm NC}_{\mu}(x) = (1 - 2\sin^2\theta_W)V^3_{\mu}(x) - 2\sin^2\theta_W V^{\rm s}_{\mu}(x) - A^3_{\mu}(x)$$
$$= V^3_{\mu}(x) - 2\sin^2\theta_W J^{\rm EM}_{\mu}(x) - A^3_{\mu}(x) \ ,$$

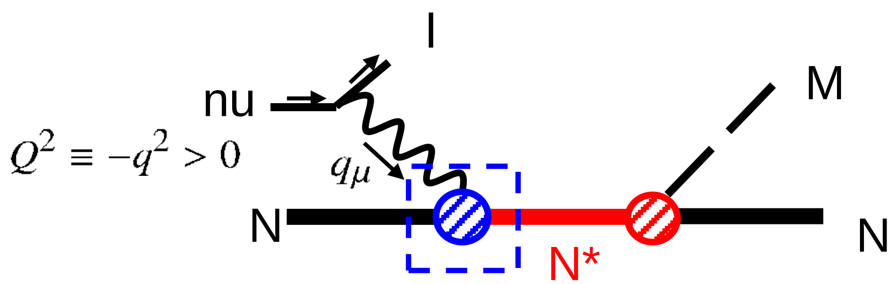
- Isobar-model

- Coupled channel model

  - Single pion production
  - Double pion production

Isobar-model

Resonance amplitude



- Mass, width *

- MN-N* coupling constants: Branching ratio *

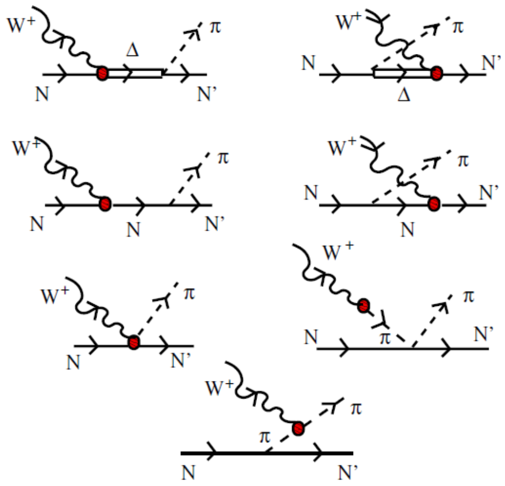
- Excitation of N* by weak current
  - V N-N* Helicity amplitude **, ***
  - A N-N* PCAC or Quark model

* RS,LPP:PDG
** RS: PDG
*** LPP: N* form factor by Jlab-Yerevan analysis

RS D. Rein L. M. Sehgal, Ann. Phys. 133, 79 (1981)
LPP O. Lalakulich,E.A. Paschos,G. Piranishvili, PRD74, 014009 (2006)
P33(1232),P11(1440),D13(1520),S11(1535)

Delta(1232) + Non-res based on chiral Lagrangian

E. Hernandez, J. Nieves, M. Valverde (HNV) PRD76, 033005(2007)



$$\mathcal{L}_{N\pi} = \bar{\Psi} i \gamma^{\mu} [\partial_{\mu} + \mathcal{V}_{\mu}] \Psi - M \bar{\Psi} \Psi + g_A \bar{\Psi} \gamma^{\mu} \gamma_5 \mathcal{A}_{\mu} \Psi + \frac{1}{2} \mathrm{Tr}[\partial_{\mu} U^{\dagger} \partial^{\mu} U],$$

Delta, N* + phen. Non-res.

T. Leitner,O. Buss, L. Alvarez-Ruso, U. Mosel PRC79,034601(2009)

$$\frac{d\sigma_{\mathrm{BG}}^{V}}{d\omega\, d\Omega_{k'}\, d\Omega_{k_\pi}} = \frac{d\sigma_{N\pi}^{V}}{d\omega\, d\Omega_{k'}\, d\Omega_{k_\pi}} - \sum_R \frac{d\sigma_{\ell N \to \ell R \to \ell N\pi}^{V}}{d\omega\, d\Omega_{k'}\, d\Omega_{k_\pi}}$$

$$d\sigma_{\mathrm{BG}} = d\sigma_{\mathrm{BG}}^{V} + d\sigma_{\mathrm{BG}}^{\text{non-V}} = (1 + b^{N\pi})\, d\sigma_{\mathrm{BG}}^{V},$$

HNV model + partial unitarity(P33 wave)

L. Alvarez-Ruso, E. Hernandez, J. Nieves, M. J. Vicente Vacas, PRD93, 014016 (2016)

$$T_{\pi N, JN} = T_{\pi N, JN}(non - res) + e^{i\Psi} T_{\pi N, JN}(res)$$

Data of meson production reactions $\pi N, \gamma N, e - N$ have to be examined within the model.

Dynamical Coupled Channel Approach

Developed for N* physics: spectrum of excited nucleon, hyperon, transition form factors from the meson production reactions

SAID-GW, Bonn-Gachina, Jeulich-Bonn, ANL-Osaka

start from Hamiltonian of meson-baryon system

‘excited nucleon’ $|N^* >$

continuum $|\pi N >, |\eta N >, |K\Lambda >, |K\Sigma >, |\pi\pi N >$

interaction $\Gamma_{N^* \leftrightarrow MB}$ $V_{MB,M'B'}$

→ Solve scattering equation that satisfies three-body unitarity

A. Matsuyama, TS, T.-S.H. Lee Phys. Rep. 439 (2007) 193

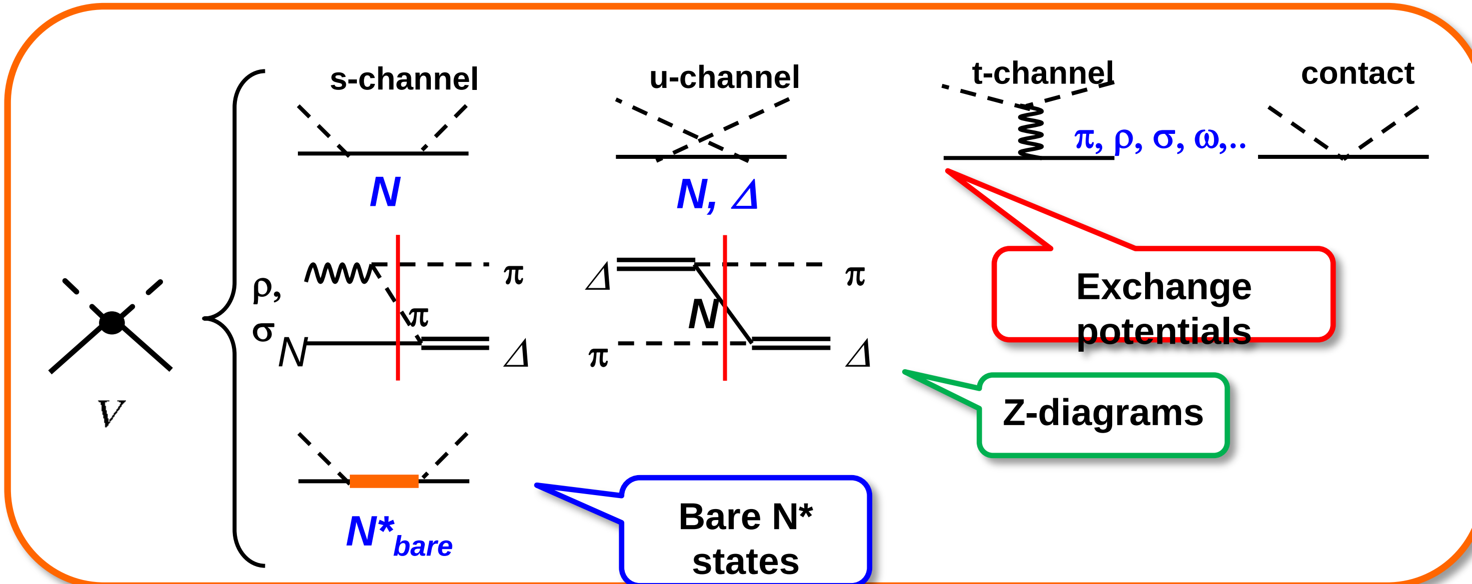
Brief description of DCC model

Fock Space

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

$\pi\pi N$

Interaction



Solve LS equation, three-body unitarity is satisfied.

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

coupled-channels effect

	(JLMS) **2006-2009**	(ANL-Osaka) **2010-2013**
channels	**6 channels**	**8 channels**
reactions	**(γN,πN,ηN,$\pi\Delta$,ρN,σN)**	**(γN,πN,ηN,$\pi\Delta$,ρN,σN,KΛ,KΣ)**
✓ **πp → πN**	**W < 2 GeV**	**< 2.3 GeV**
✓ **γp → πN**	**< 1.6 GeV**	**< 2 .1GeV**
✓ **π-p → ηn**	**< 2 GeV**	**< 2.1 GeV**
✓ **γp → ηp**	—	**< 2.1 GeV**
✓ **πp → KΛ, KΣ**	—	**< 2.1 GeV**
✓ **γp → KΛ, KΣ**	—	**< 2.1 GeV**

- ***Extended to include KY production reaction, higher W***
- ***Fully combined* analysis of γN , πN → πN , ηN , KΛ, KΣ reactions**
  SU(3) Meson (P,V octet), Baryon(octet,decuplet)
- **omega N, pipi N are not included in fit**
- **Total 22,348 data points**

(JLMS)B. Julia-Diaz,T.-S. H.Lee,A. Matsuyama, T. Sato,PRC76 065201(2007)

model for Neutrino-nucleon interaction

S.X.Nakamura, H. Kamano, TS PRD92,074024(2015)

DCC model from Delta up to W < 2GeV (DIS: W>2GeV, $Q^2 > 1\sim2GeV^2$)

previous model for Delta(1232) N + pi

TS, Uno, T.-S. H. Lee, PRC67,065201(2003), K.Matsui,TS,T.-S. H. Lee PRC72,025204(2005)

Extension of ANL-Osaka DCC Model(2013) for neutrino reaction

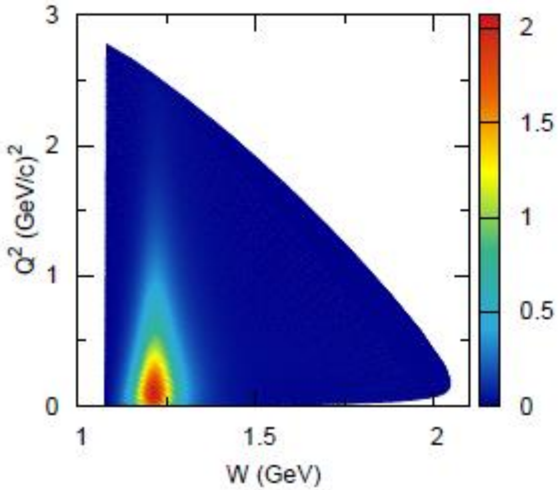
H. Kamano, S.X. Nakamura,T. –S. H. Lee, TS,PRC88,035209(2013)

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

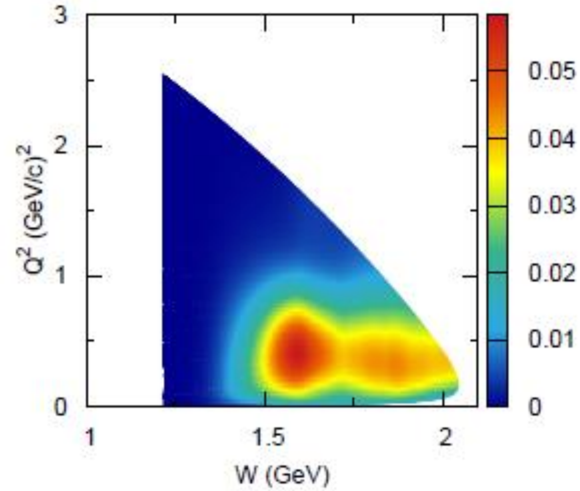
- Axial vector current : PCAC $g_{\pi NN^*} \rightarrow g_{ANN^*}$,
  assume dipole form factor for Q^2 dependence

Overview of neutrino induced reaction (DCC model) $E_\nu = 2GeV$

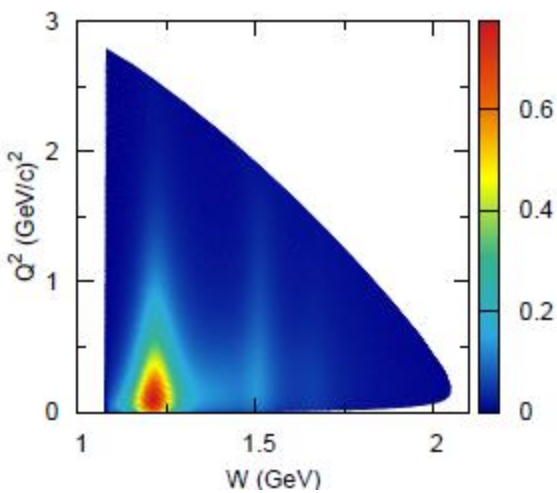
$$\nu_\mu + p \to \mu^- + \pi^+ + p$$



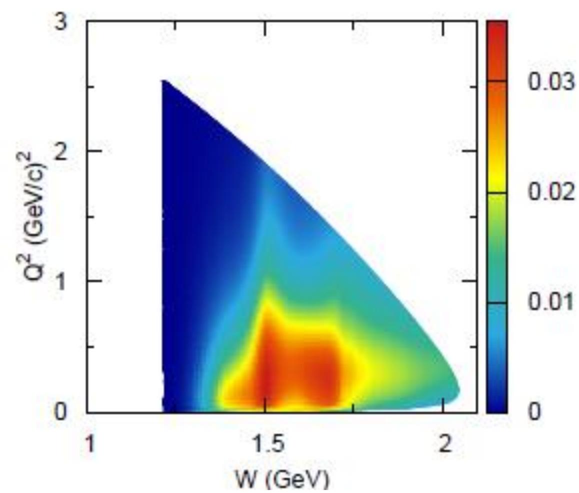
$$\nu_\mu + p \to \mu^- + \pi^+ + \pi^0 + p$$



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



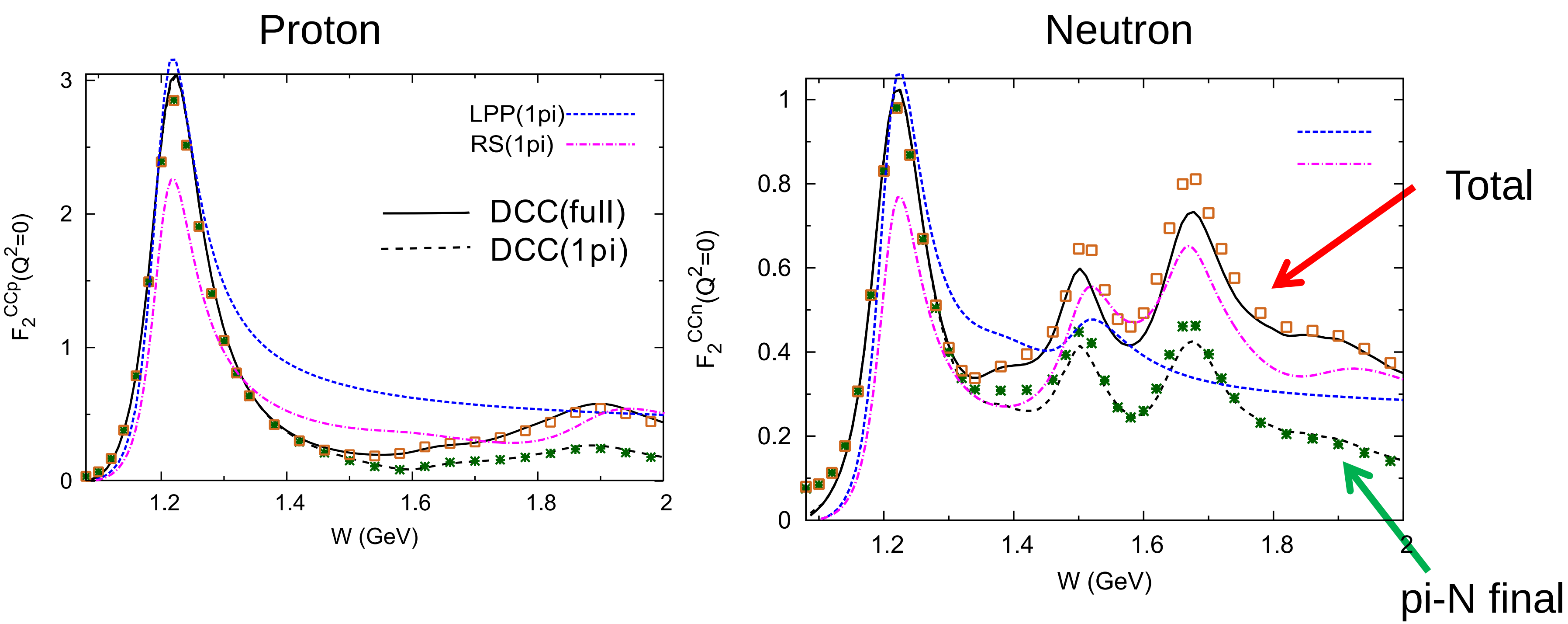
$$\nu_\mu + n \to \mu^- + \pi^+ + \pi^- + p$$



inclusive cross section

structure function CC F_2 at $Q^2=0$

only Axial vector contributes, using PCAC $F_2 = \frac{2f_\pi^2}{\pi}\sigma(\text{virtual}\pi + N)$



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.

Compilation of Low energy ($E < 30 GeV$) Neutrino Cross Section

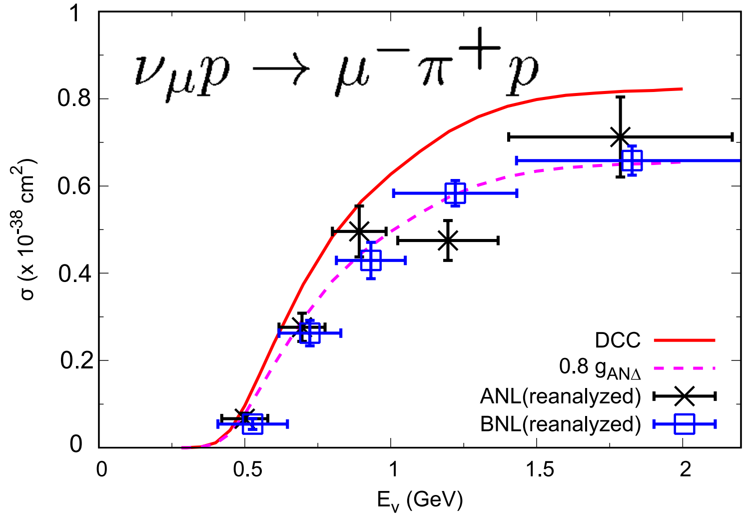
(http://hepdata.cedar.ac.uk/review/neutrino/)

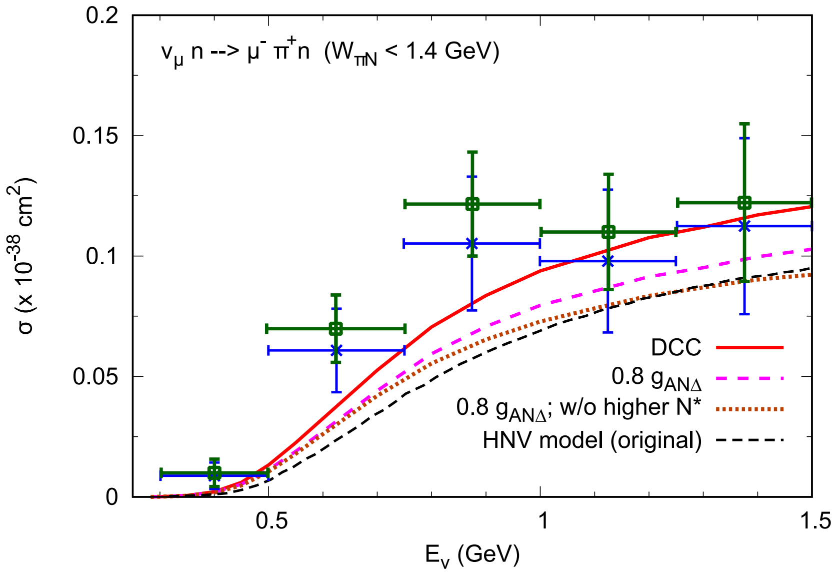
			1	2
GGM	Lerche 1978	Propane	1-10	
	Bolognese 1979	Propane-Freon	1-7.5	
BEBC	Allen 1986	p	10-80	
	Allasia 1990	d	5-150	
BNL	Kitagaki 1986	d	0.5 - 3	0.5 - 3
ANL	Barish 1979	p,d	0.4 - 6	
	Radecky 1982	d	0.5 - 1.5	
	Day 1983	d		0.75-5.55
FNAL	Bell 1978	p	15-40	
SKAT	Ammosov 1988	Freon(CF_3Br)	4-18	
	Grabosch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

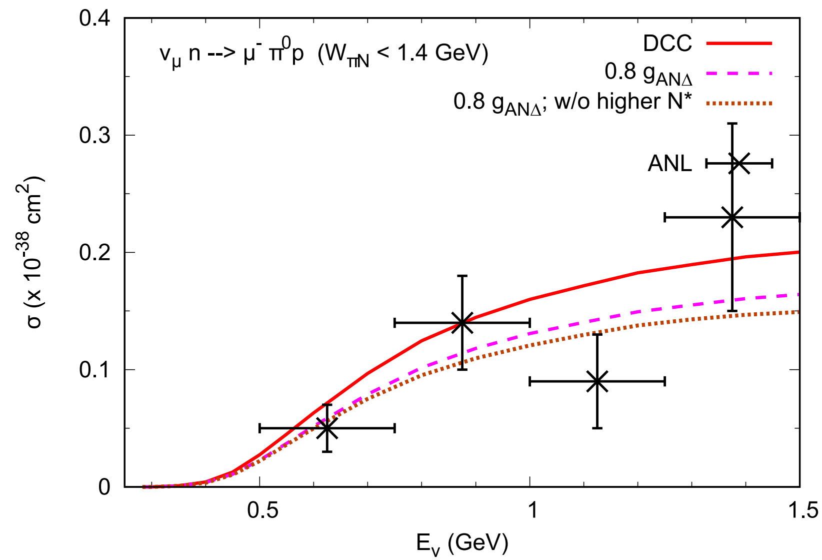
Reanalysis of ANL/BNL data
(C. Wilkinson et al. PRD90 (2014), Rodrigues et al. arXiv:1601.01888)

Final state interaction in neutrino-deuteron reaction(Jia-jun Wu et al. PRC91 (2015))

Comparison with ANL, BNL data of single pion production(re-analyzed)

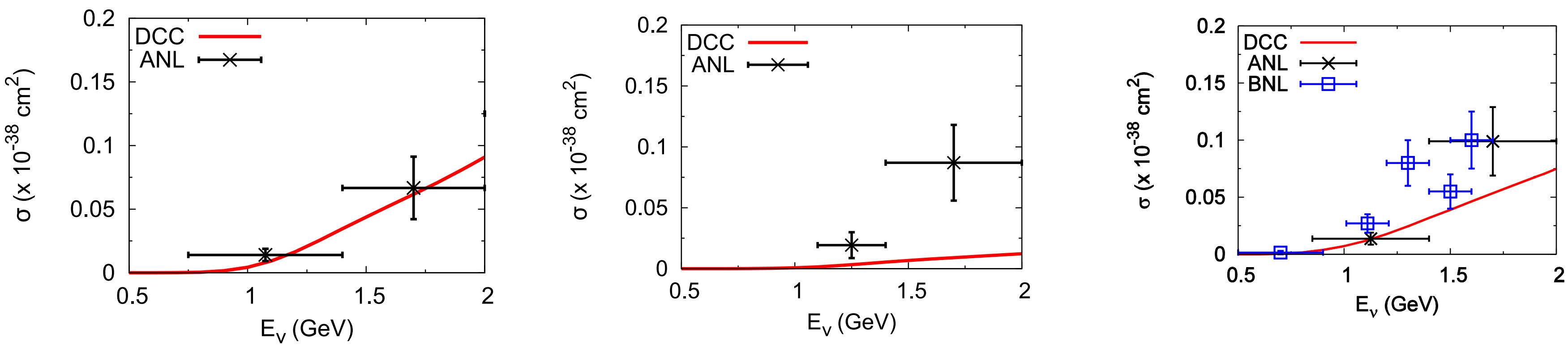




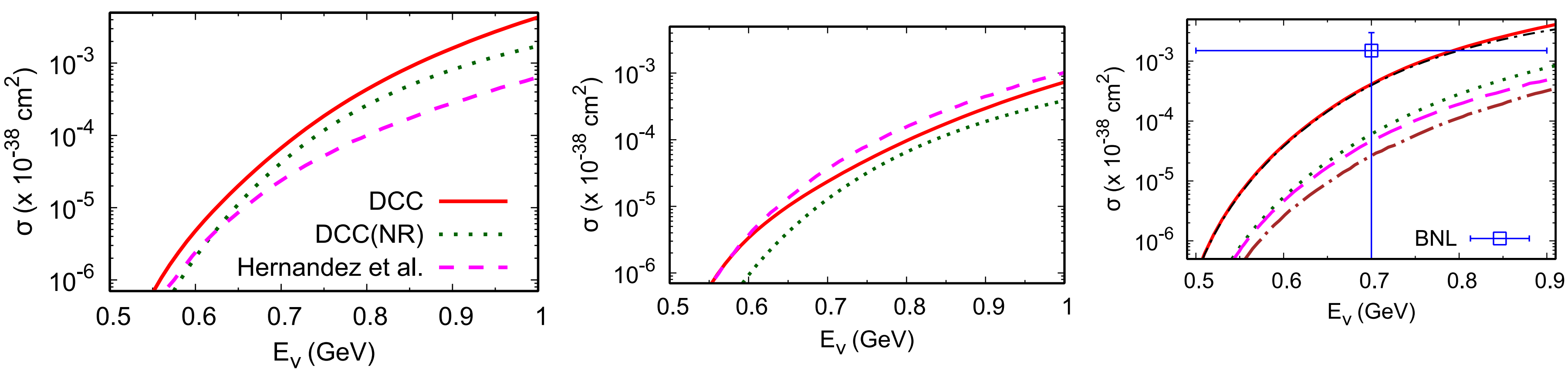


Neutrino-induced two-pion production

$\nu_\mu p \rightarrow \mu^- \pi^+ \pi^- p$ $\qquad$ $\nu_\mu p \rightarrow \mu^- \pi^+ \pi^+ n$ $\qquad$ $\nu_\mu n \rightarrow \mu^- \pi^+ \pi^- n$



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



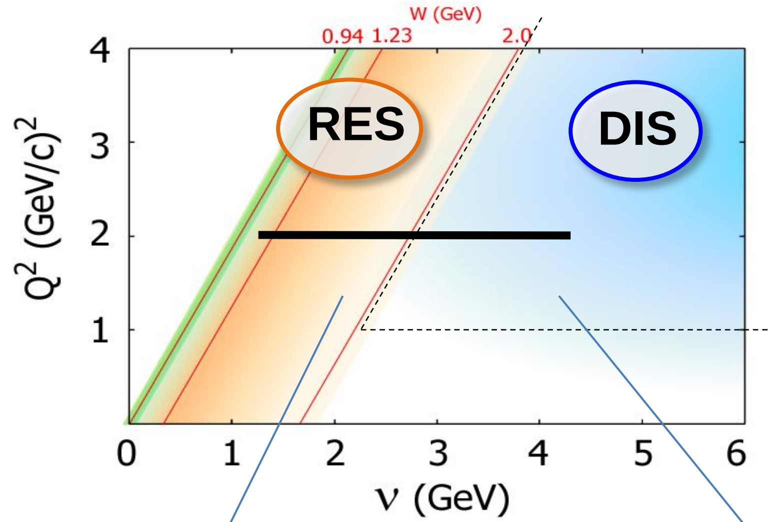
E. Hernandez,J. Nieves,S. K. Singh, M. Valverde, M. . Vicente Vacas
PRD77,053009(2008)

Summary of models for neutrino reaction in RES

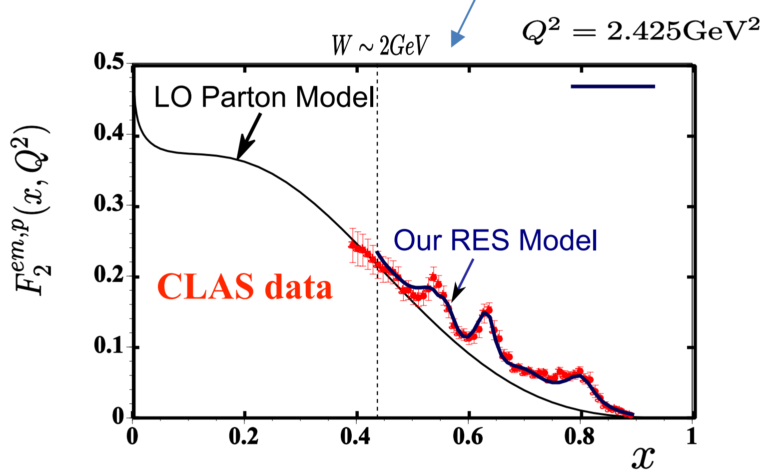
	Res	Non-res	Unit.	1pi	2pi	Tot
RS	Delta,N*	-	X	O		O
LPP	Delta,N*	X	X	O		O
HVM	Delta(1232)	chiral	O	O		
	Delta(1232)+N(1440)	chiral	X	O	O	
Giessen	Delta, N*	phen.	X	O		O
ANL-Osaka	Delta, N*	O	O	O	O	O

Matching with DIS region

Energy transfer vs momentum transfer



Vector current



Axial vector current

?

Working now

Summary

Model of weak meson production reactions including two-pion production channel for $W<2$GeV, $Q^2<3$ 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 case) regions

Models for neutrino induced meson production reaction has to be tested against all available data of pion and electromagnetic probes.

For precise tests of theoretical approaches (reaction models, chiral perturbation theory for axial vector coupling constant, ..), more data is needed. At the same time, theoretical tools to analyze deuteron reaction should be prepared.