Neutrino induced meson production reaction in the resonance region

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Introduction

'Neutrino induced meson production reactions on nucleon' based on

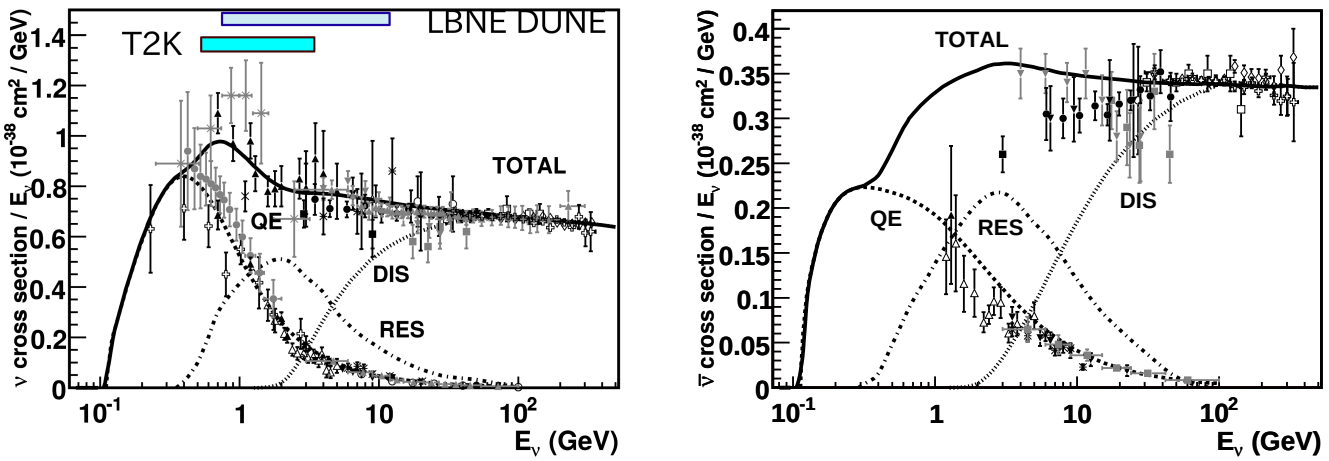
- pion production in neutrino-deuteron (pion production, Δ)
  Phys. Rev. C91, 035203 (2015), Jia-Jun Wu, T. Sato, T. -S. H. Lee
- Coupled channel model for neutrino induced meson production reactions ($\pi, \pi\pi, K, \eta$ production, Δ, N^*)
  Phys. Rev. D92, 074024 (2015), S.X. Nakamura, H. Kamano, T. Sato

collaboration : JPARC branch, Theory center of KEK: Y. Hayato,M. Hirai, H. Kamano, S. Kumano, T. Murata, S.X. Nakamura, K. Saito, T. Sato,M. Sakuda

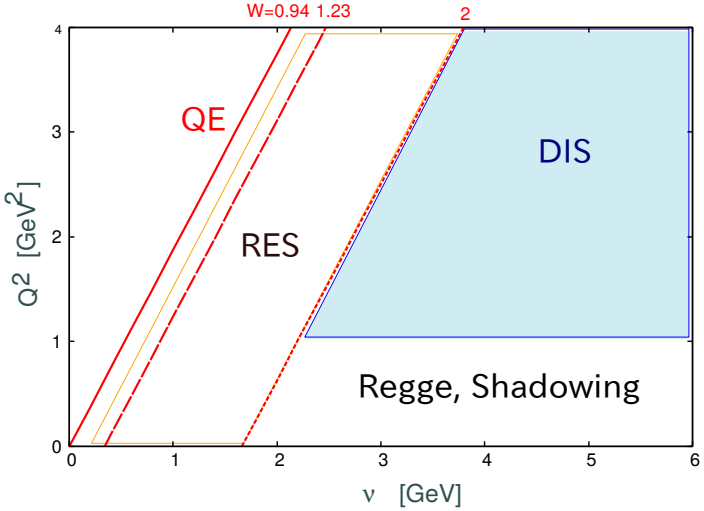
- Introduction
- Neutrino induced meson production reaction in resonance region
  (DCC model, extension for neutrino reaction)
- Results of DCC model for neutrino reaction
- Single pion production

Reaction mechanism

ν $\bar{\nu}$



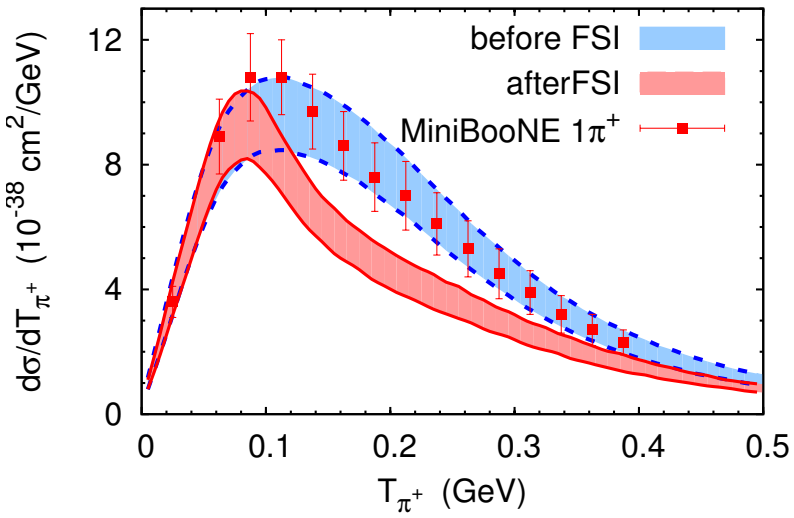
J. A. Formagglo and G. P. Zeller Rev. Mod. Phys. 84 (2012) 1307.

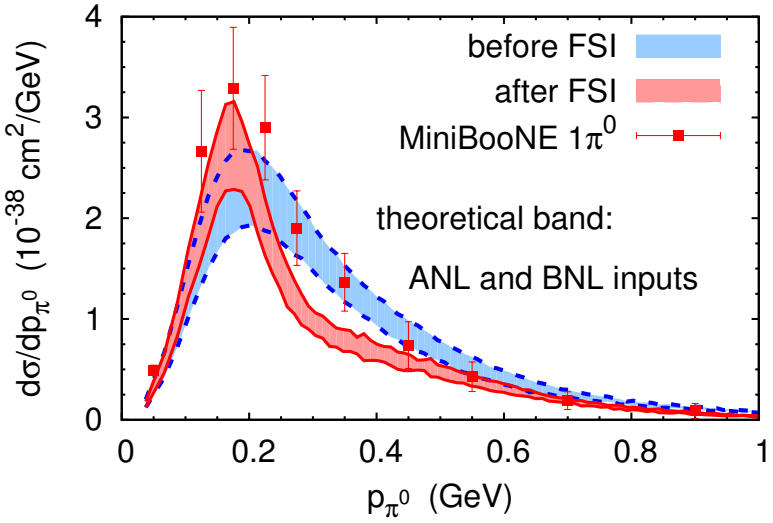


RES $m_N + m_\pi < W < 2GeV$ DIS $W > 2GeV, Q^2 > 1(GeV/c)^2$

Neutrino-Nucleus pion production reaction

MiniBooNE data and GiBUU results





(Taken from U. Mosel, arXiv 1602.00696)

- Need further study on the mechanism of neutrino-induced pion production and pion interaction in a few GeV range.

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

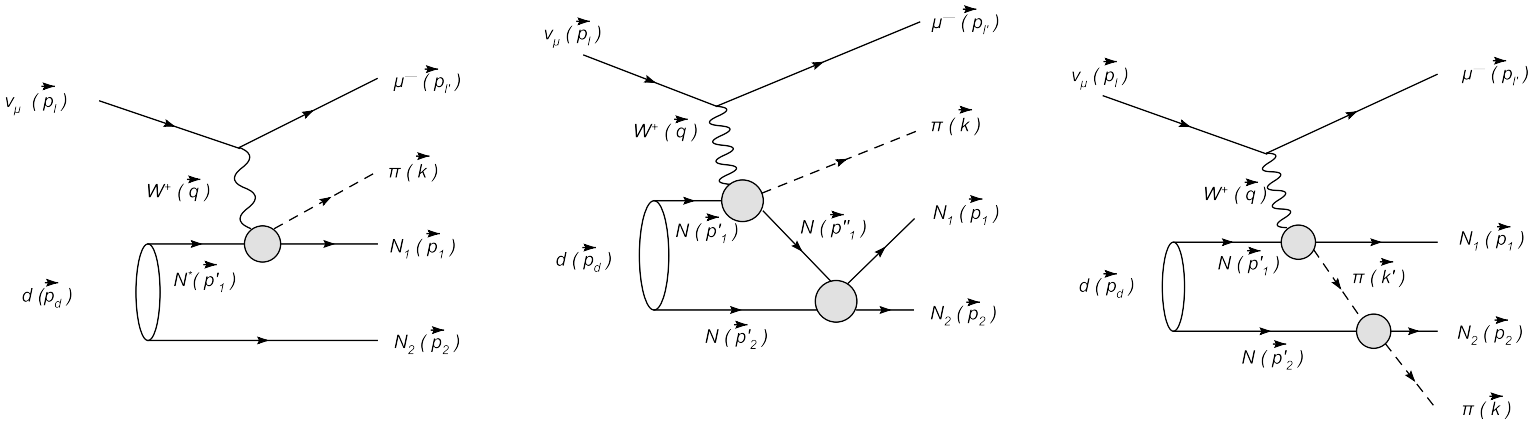
				1π	2π
GGM	Lerche 1978	ν	Propane	1-10	
	Bolognese 1979	$\bar{\nu}$	Propane-Freon	1-7.5	
BEBC	Allen 1986	ν	p	10-80	
	Allasia 1990	$\nu, \bar{\nu}$	d	5-150	
BNL	Kitagaki 1986	ν	d	0.5 - 3	0.5 - 3
ANL	Barish 1979	ν	p,d	0.4 - 6	
	Radecky 1982	ν	d	0.5 - 1.5	
	Day 1983	ν	d		0.75-5.55
FNAL	Bell 1978	ν	p	15-40	
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)
- Final state interaction in neutrino-deuteron reaction(Jia-jun Wu et al. PRC91 (2015))

Final state interaction in $\nu - d$ reaction

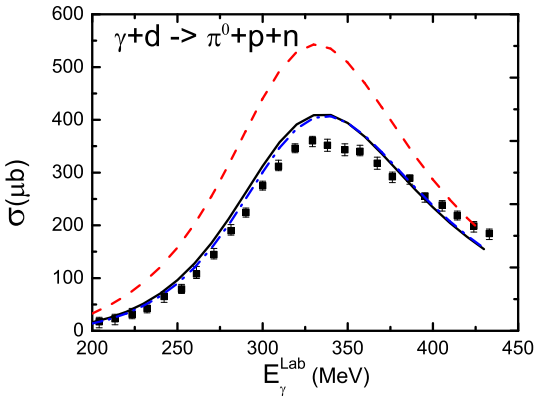
Jia-jun Wu et al. PRC91 (2015)

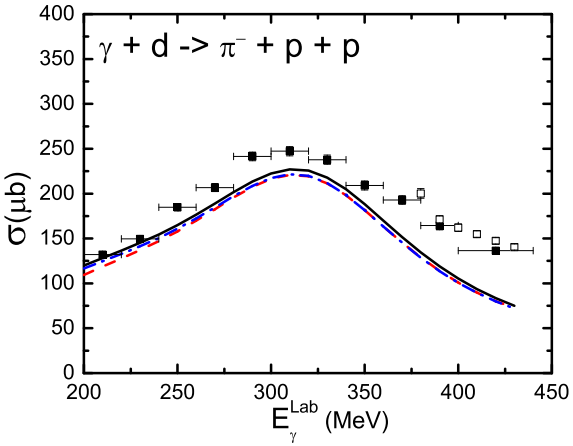
- ANL,BNL data are from neutrino-deuteron reaction.
  No many body effects are taken into account to extract $\nu - N$ cross section.
- final state interactions are known to be important for $d(\gamma, \pi)NN$



Estimation of final state interaction(rescattering):
* $\pi N, (\gamma, \pi), p(e, e'\pi)N$ and $N(\nu, l\pi)N$ in delta-resonance region:Sato,Uno,Lee PPC67(03),Matsui,Sato,Lee PRC72(05)
* NN interaction:Bonn potential

Pion photoproduction (red IA, green IA+NN, blue IA+pi+NN)

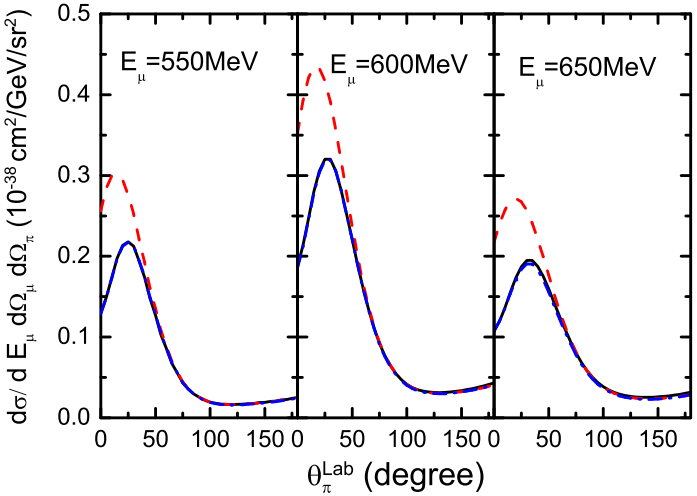


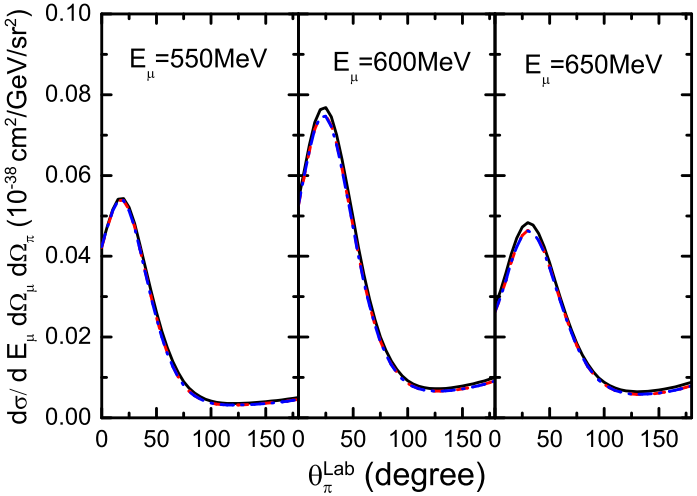


- Large NN rescattering effects for $\gamma + d \to p + n$

Neutrino induced pion production($E_\nu = 1GeV, \theta_\mu = 25^o \sim$ QE production of Δ)

$$\nu_\mu + d \to \mu^- + \pi^+ + p + n \qquad \nu_\mu + d \to \mu^- + \pi^0 + p + p$$





- Large NN rescattering effects for pn final state not pp.
- Scattering pn wave function ($^3S_1 -^3 D_1$) must be orthogonal to d.

Neutrino induced meson production reaction in resonance region (Δ, N^*)

Isobar Model (Tree diagrams)

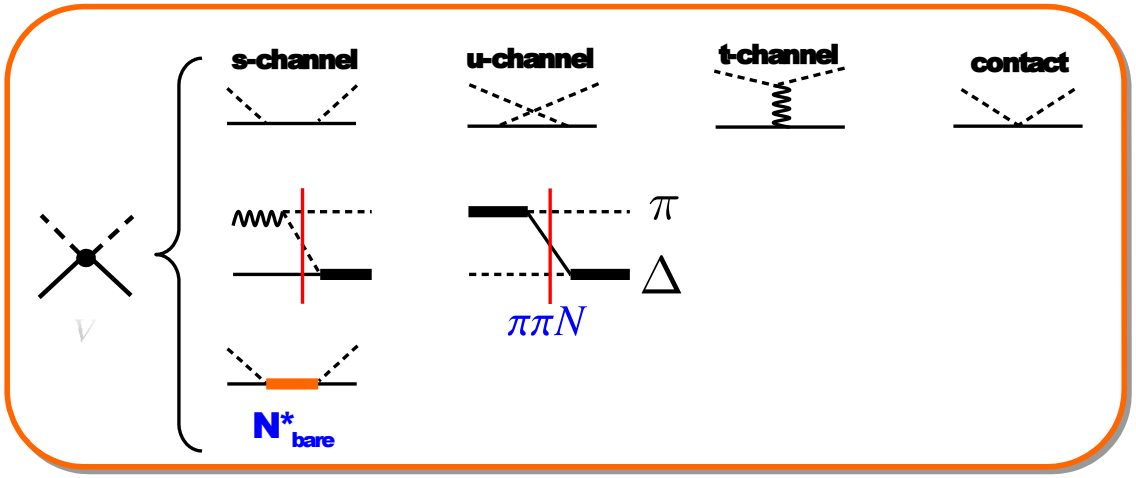
- Rein-Sehgal Ann. Phys. 133 (80), Z. Phys (87)
- Alvarez-Ruso et al. PRC57(98)
- Paschos et al. PRD65(02), Lalakulich et al. PRD71(05),PRD74(06)
- Hernandez et al. PRD76(07),PRD81(10), Lalakulich et al. PRD82(10)

Coupled channel approach (Unified description of $\pi N, \gamma^* N \to \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$ reactions)

- Δ region: Sato,Uno,Lee PPC67(03),Matsui,Sato,Lee PRC72(05)
- $N*$ region:Nakamura,Kamano,Sato PRD92(15)

Brief explanation of Coupled-channel model

Start from interaction Hamiltonian for meson-baryon system
$(N^*, \Delta, \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N(\rho N, \pi\Delta, \sigma N)\ )$



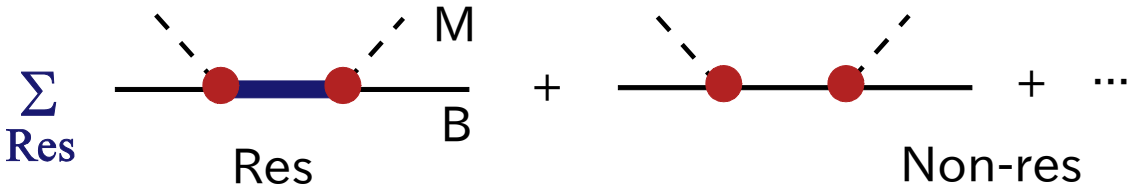
then solve Lippmann-Schwinger Equation.

$$T = V + VG_0T$$

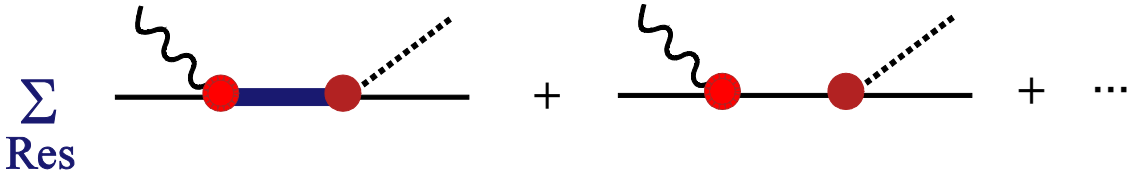
From pion and photon induced reaction to neutrino reaction

Coupled-channel model for πN and γN (Kamano, Nakamura, Lee, Sato PRC88(13))

- Pion induced reaction(proton)



- Photon induced reaction(proton)



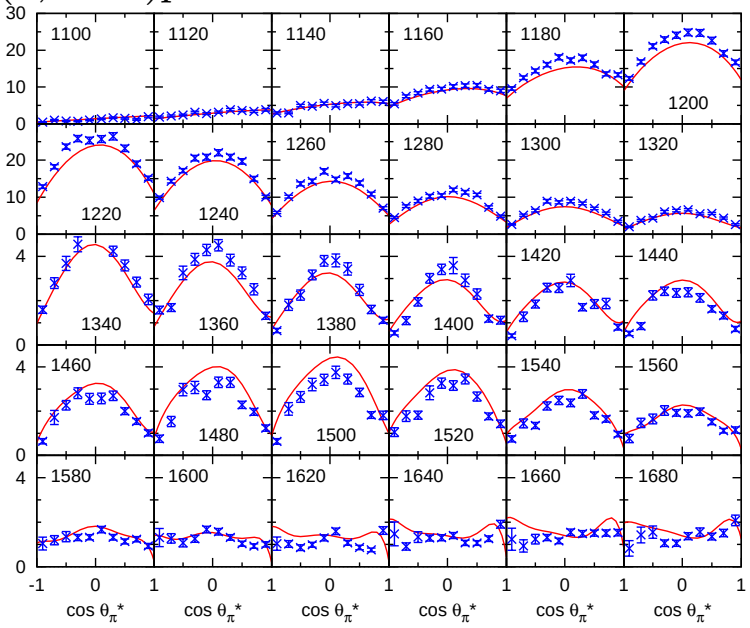
Extension for neutrino reaction (Nakamura,Kamano, Sato(2015))

- Vector current
  $V^\mu_{em} = V^\mu_{IS} + V^\mu_3 \;\leftrightarrow\; V^\mu_{CC} = V^\mu_1 + iV^\mu_2$:(γn) for $I = 1/2$ resonance
  Q^2 dependence of $\gamma N N*$ coupling constants: $p(e, e'\pi)$
- Axial vector current: $g_A^{NN^*}$ from $g_\pi^{NN^*}$ PCAC
  assume dipole form factor

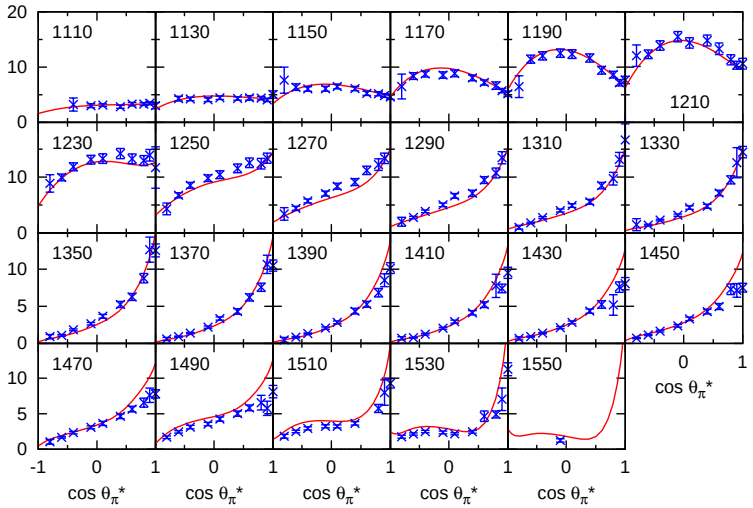
Differential cross section of pion electroproduction

$$\frac{d\sigma_T}{d\Omega} + \epsilon \frac{d\sigma_L}{d\Omega} \text{ at } Q^2 = 0.4GeV^2$$

$p(e, e'\pi^0)p$



$p(e, e'\pi^+)n$

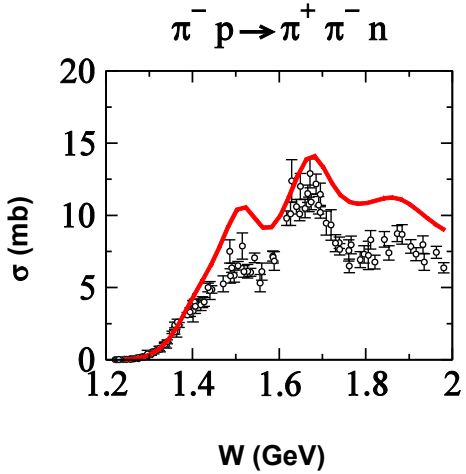


pi N → pi pi N reaction

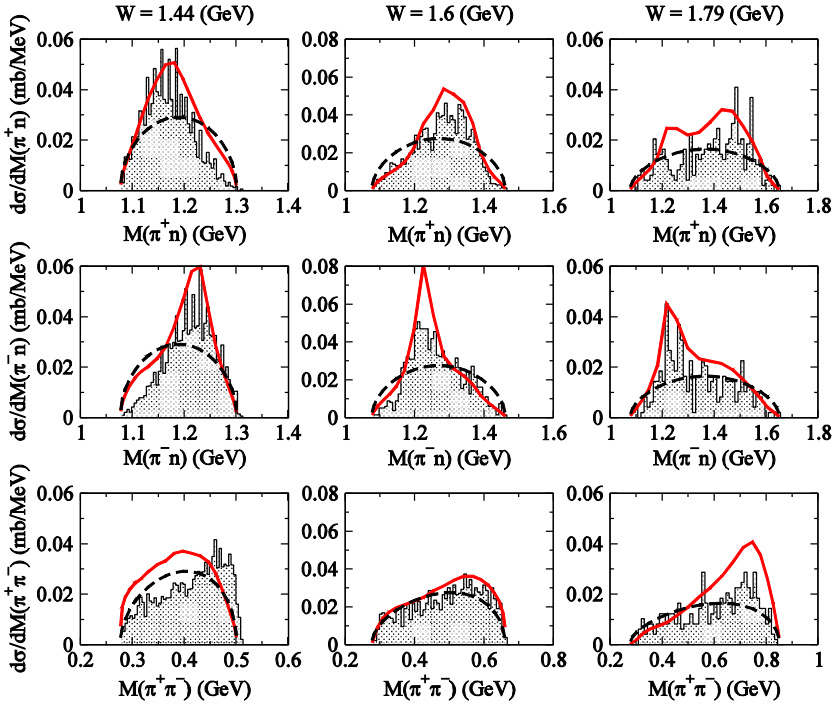
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

Parameters used in the calculation are from πN → πN analysis.

$$\pi^- p \rightarrow \pi^+ \pi^- n$$



Full result



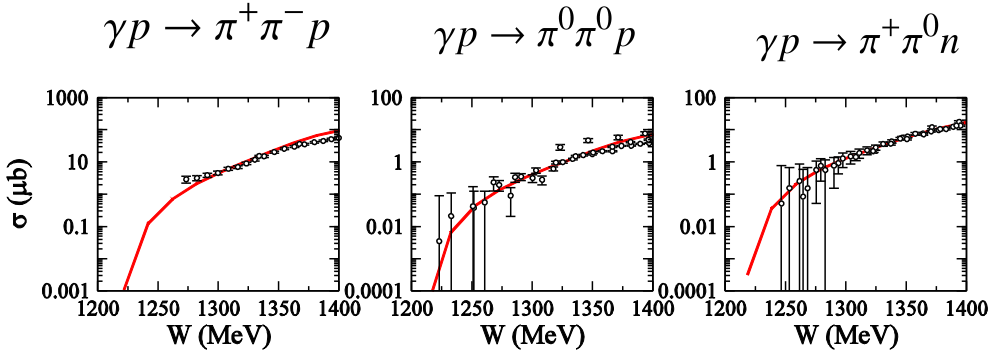
Full result Phase space

From H. Kamano

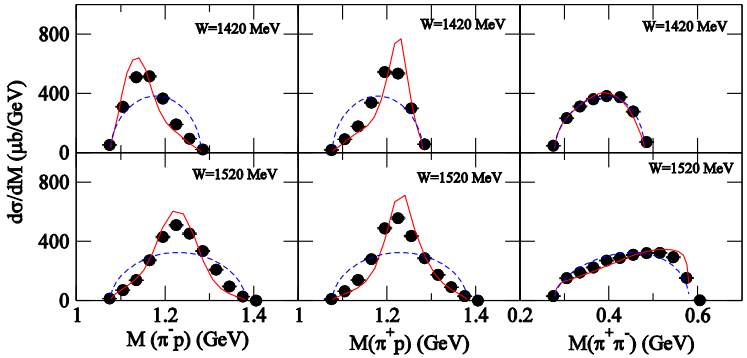
Double pion photoproduction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

Parameters used in the calculation are from πN → πN & γN → πN analyses.



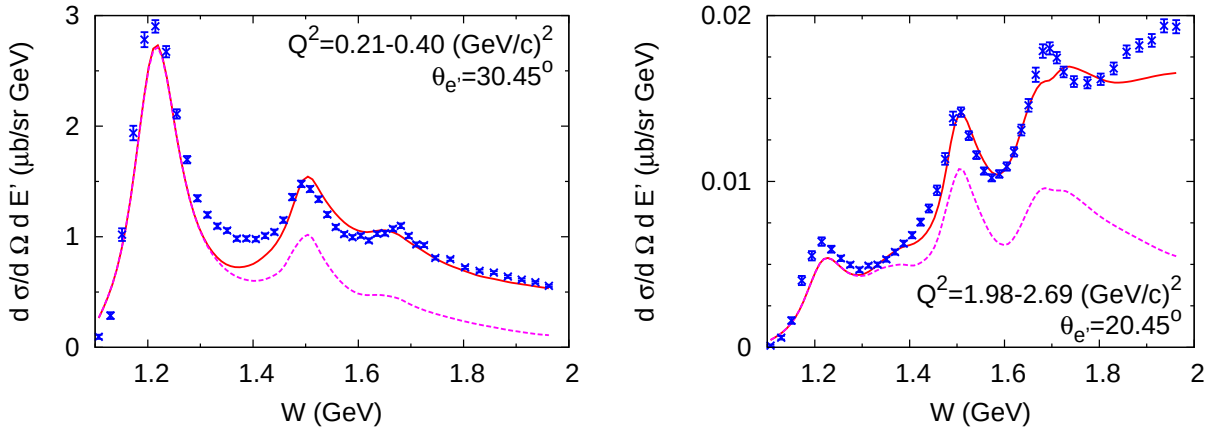
- ✓ **Good description near threshold**
- ✓ **Reasonable shape of invariant mass distributions**
- ✓ **Above 1.5 GeV, the total cross sections of $p\pi^0\pi^0$ and $p\pi^+\pi^-$ overestimate the data.**



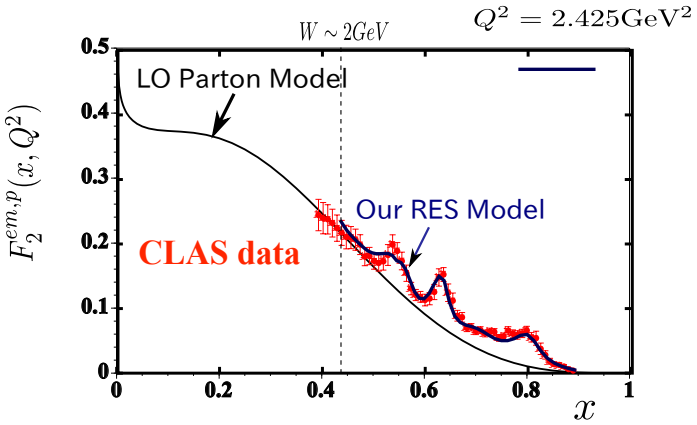
From H. Kamano

Result of DCC model for $p(e, e'X)$

Inclusive cross section(dotted: single pion production, cross:JLAB E00-002)



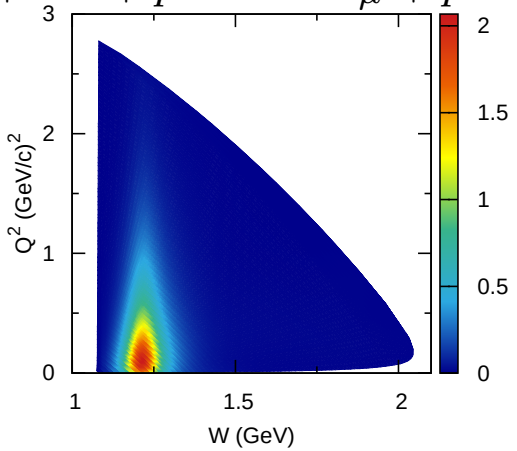
Structure function: compare with parton model



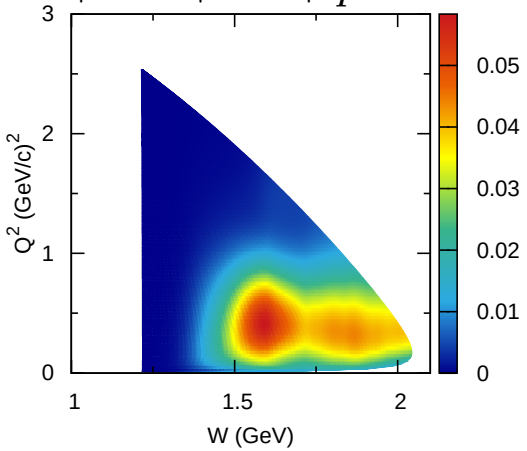
Results of DCC model for neutrino reaction

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

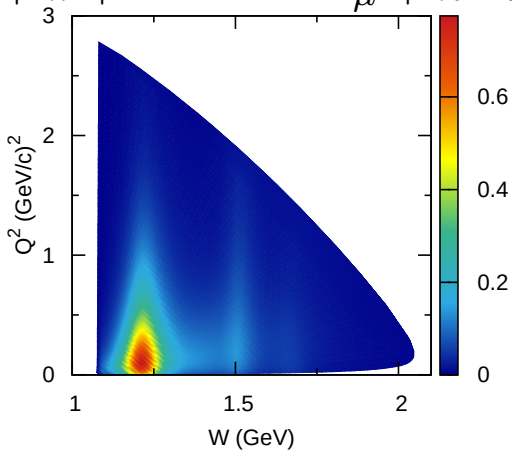
$\nu_\mu + p \to \mu^- + \pi^+ + p$



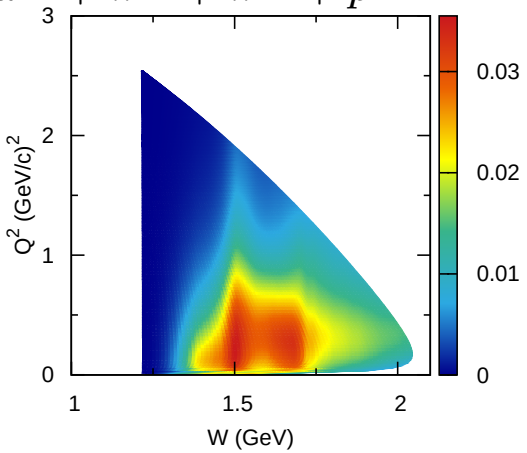
$\nu_\mu + p \to \mu^- + \pi^+ + \pi^0 + p$



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



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

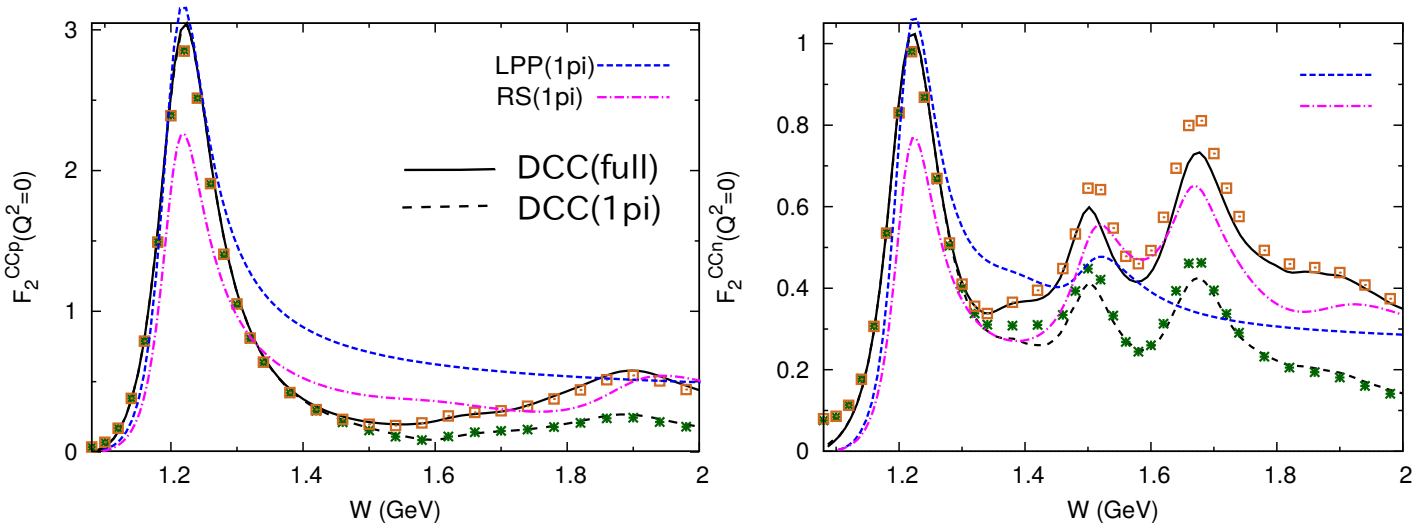


Total cross section $(Q^2 = 0, m_l = 0)$

Assume PCAC

$$\frac{d\sigma^{CC}}{dE_l d\Omega_l} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{E'^2}{E - E'} F_2, \qquad F_2 = \frac{2 f_\pi^2}{\pi} \sigma_{tot}(\pi + N)$$

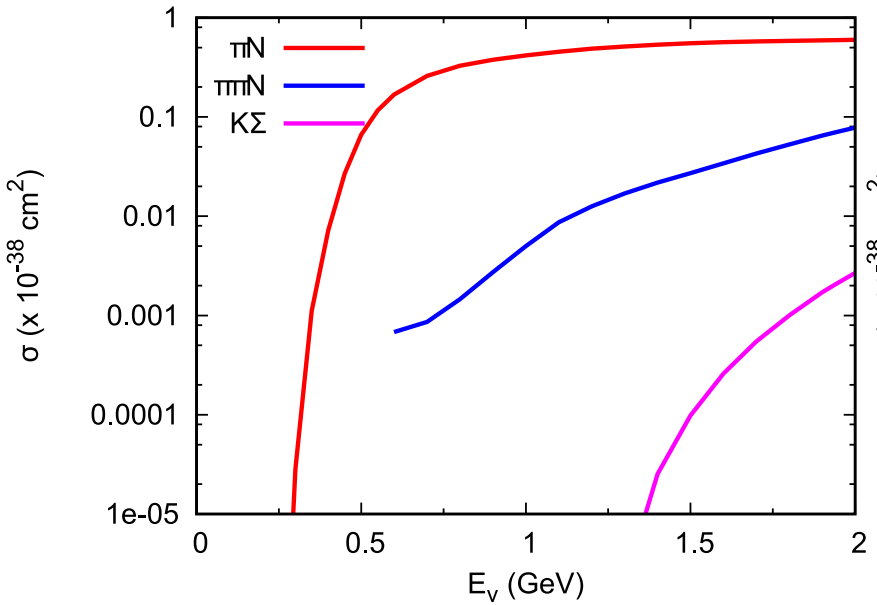
νp νn



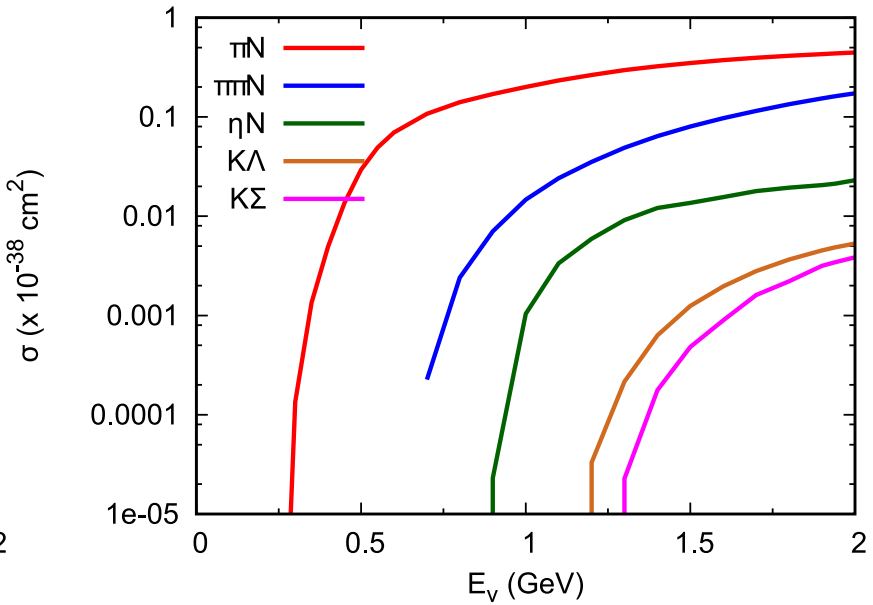
- DCC model: agree with cross section estimated from πN amplitude
- $\Delta(1232)$ + [$N^*(1535)1/2^-, N^*(1520)1/2^-$] + [$N^*(1675)5/2^-, N^*(1680)5/2^+$]
- Rein-Sehgal and Lalakulich-Paschos-Piranishvili models may predict too strong single pion production in N^* region(Axial vector current).

Production of $\pi, \pi\pi, \eta, K$(Total cross section)

$\nu_\mu + p$

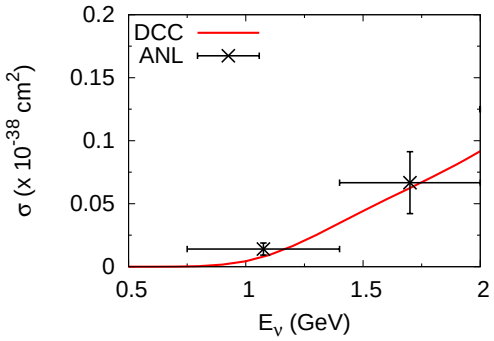


$\nu_\mu + n$

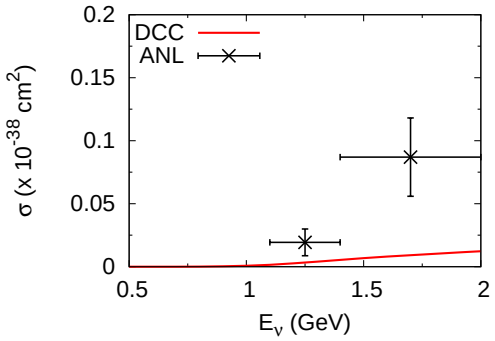


Two pion production

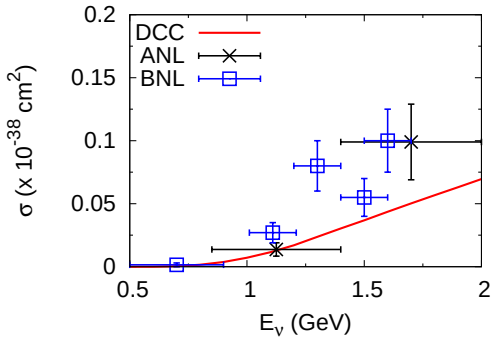
$\nu_\mu p \to \mu^- \pi^+ \pi^0 p$

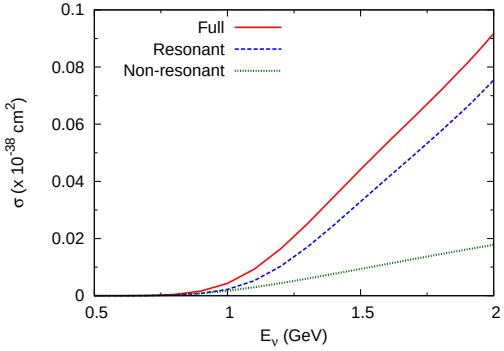


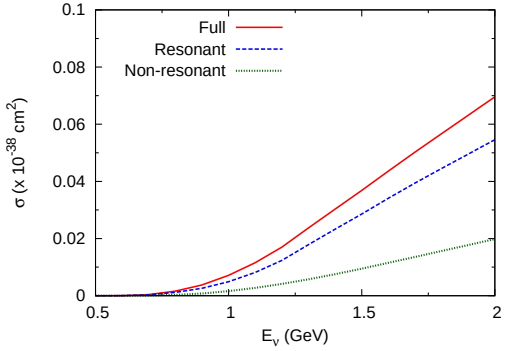
$\nu_\mu p \to \mu^- \pi^+ \pi^+ n$



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



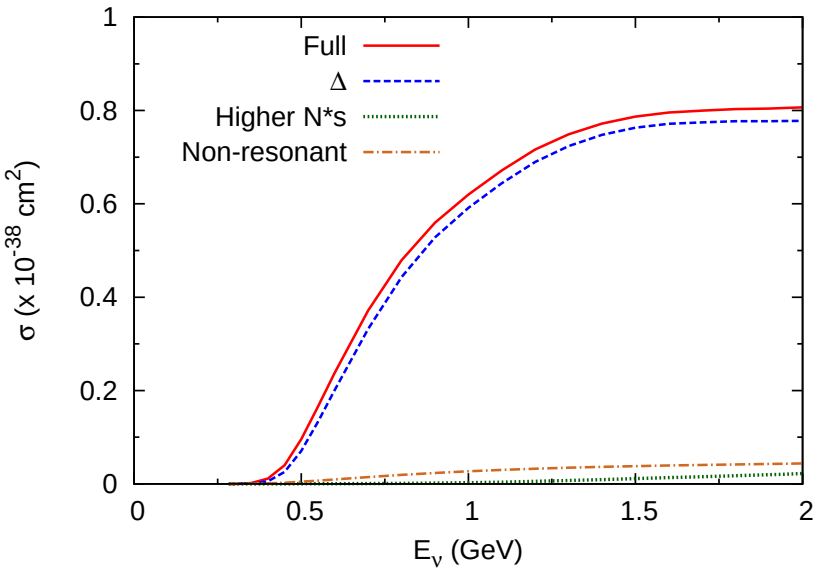




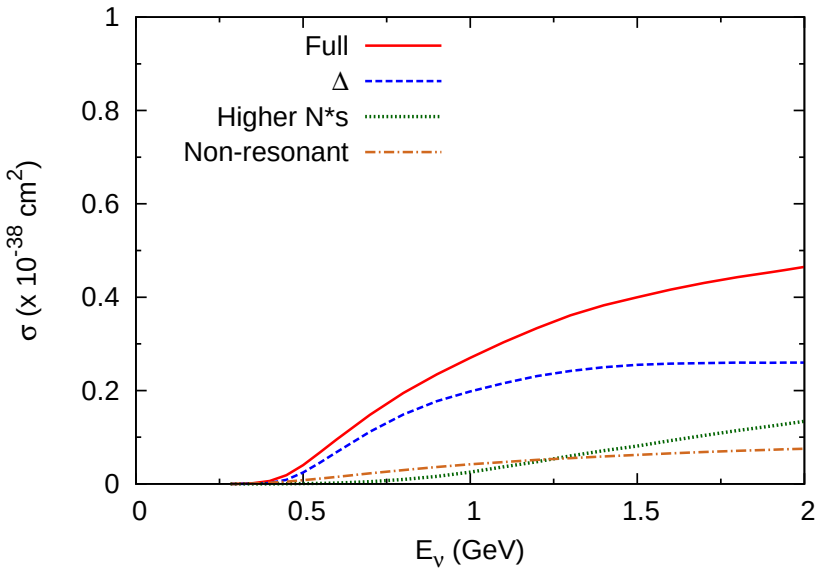
Single pion production

Resonant and non-resonant single pion production mechanism

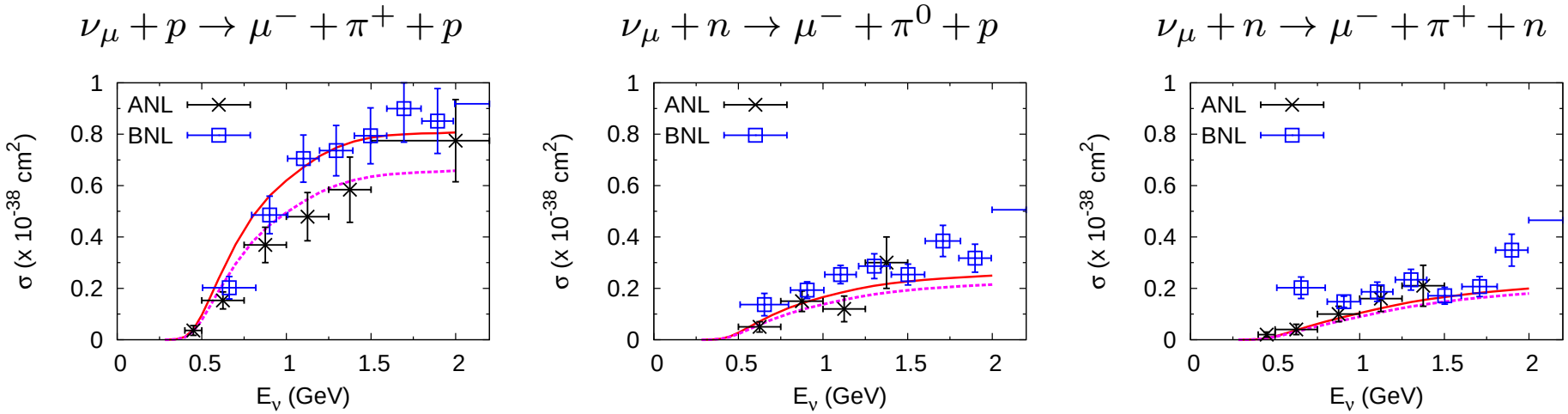
$\nu_\mu + p$



$\nu_\mu + n$

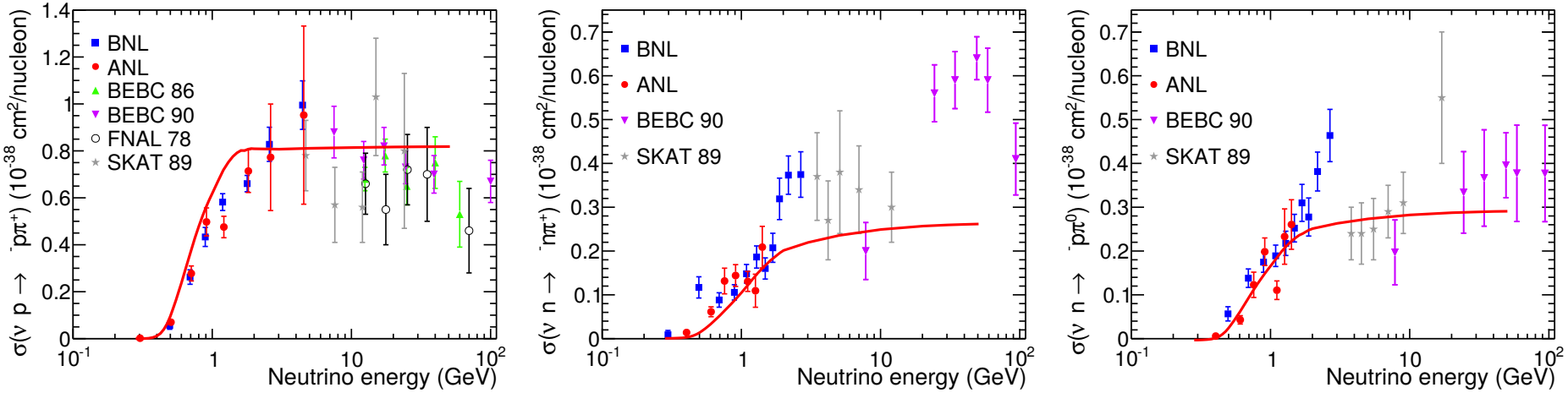


Comparison with ANL/BNL data



- $(\pi^0 p/\pi^+ p) : (\pi^+ n/\pi^+ p) = 0.29 : 0.21 (DCC, E_\nu = 1.5 GeV) \quad [= 2/9 : 1/9(\Delta)]$ deviation from Δ dominance model is due to higher N^* and non-resonant mechansim for $\nu - n$ reaction.
- Dashed curve: $0.8 \times g_{AN\Delta}(PCAC)$

Total cross section of single pion production (DCC model: $W < 2GeV, Q^2 < 2(GeV/c)^2$) Preliminary



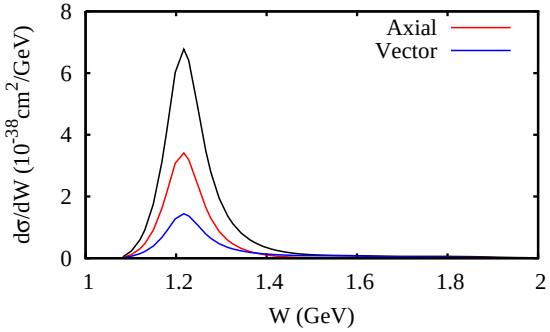
DCC model (Solid red-curve) added to Fig.11 of P. Rodrigues et al. arXiv:1601.01888

- DCC model reproduces data reasonably well.
- Note: FSI should be considered for νd data. (Nakamura et al. in progress)

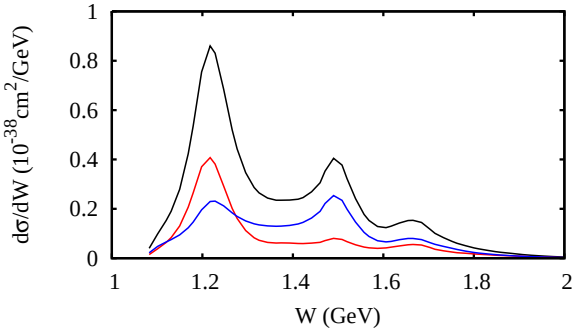
Single pion production at $E_\nu = 2GeV$ [higher N^* and $V-A$] ($d\sigma/dW = \int dQ^2 d\sigma/dW/dQ^2$)(Preliminary)

Neutrino reaction

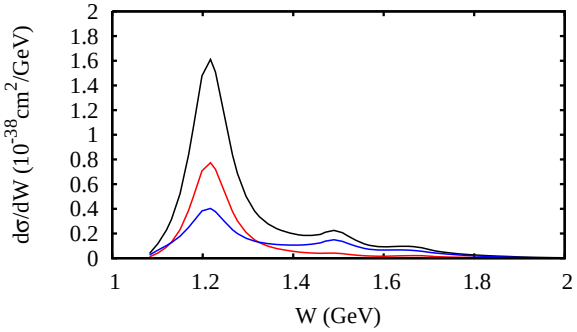
$\nu_\mu + p \to \mu^- + \pi^+ + p$



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

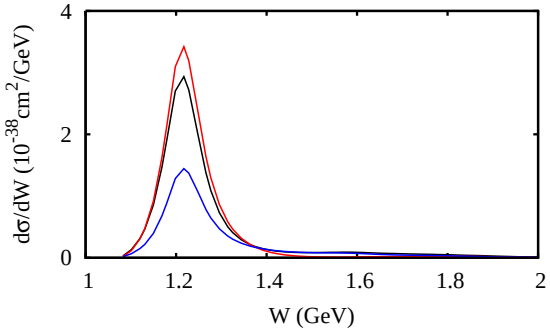


$\nu_\mu + n \to \mu^- + \pi^0 + p$

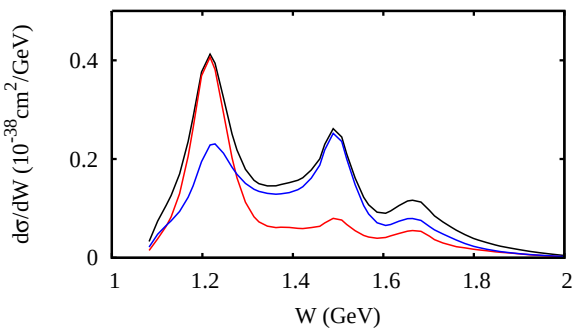


Anti-neutrino reaction

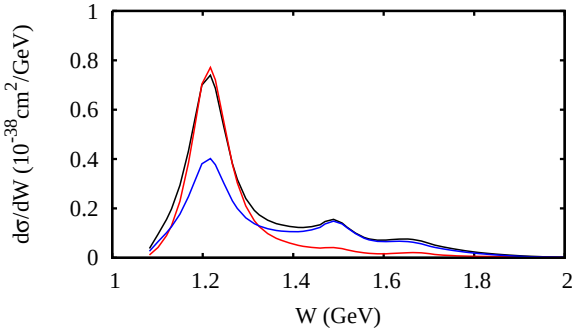
$\bar{\nu}_\mu + n \to \mu^+ + \pi^- + n$



$\bar{\nu}_\mu + p \to \mu^+ + \pi^- + p$

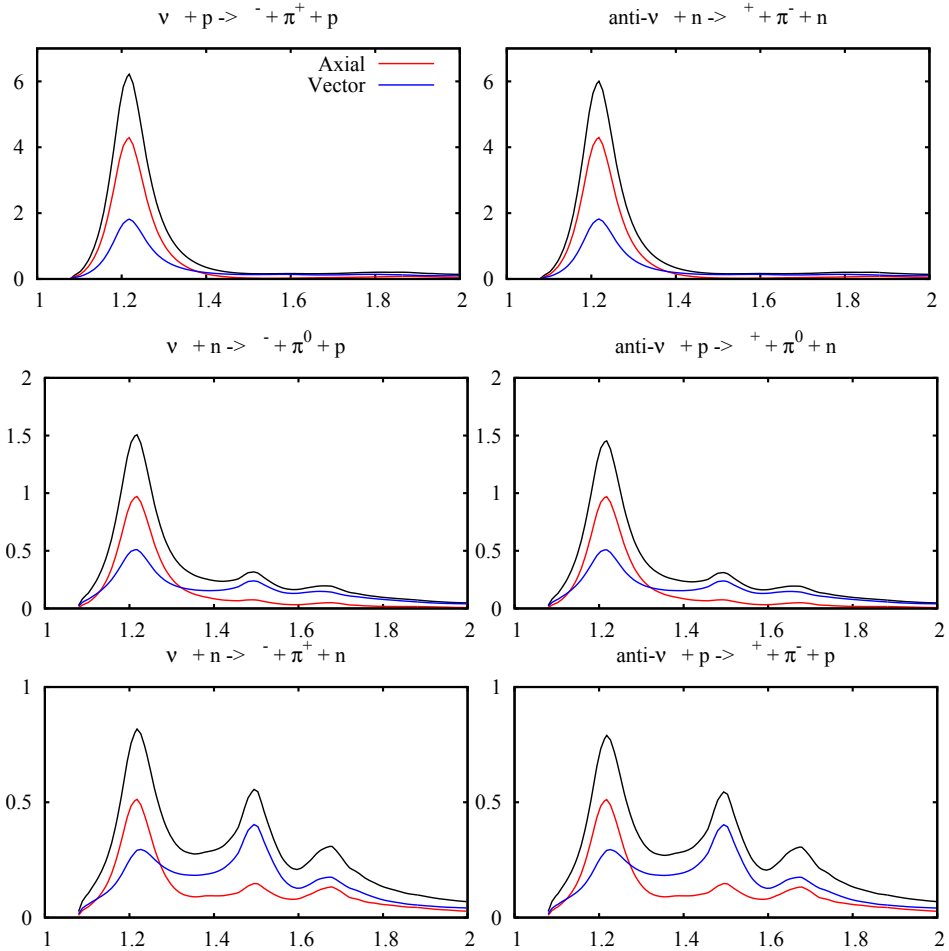


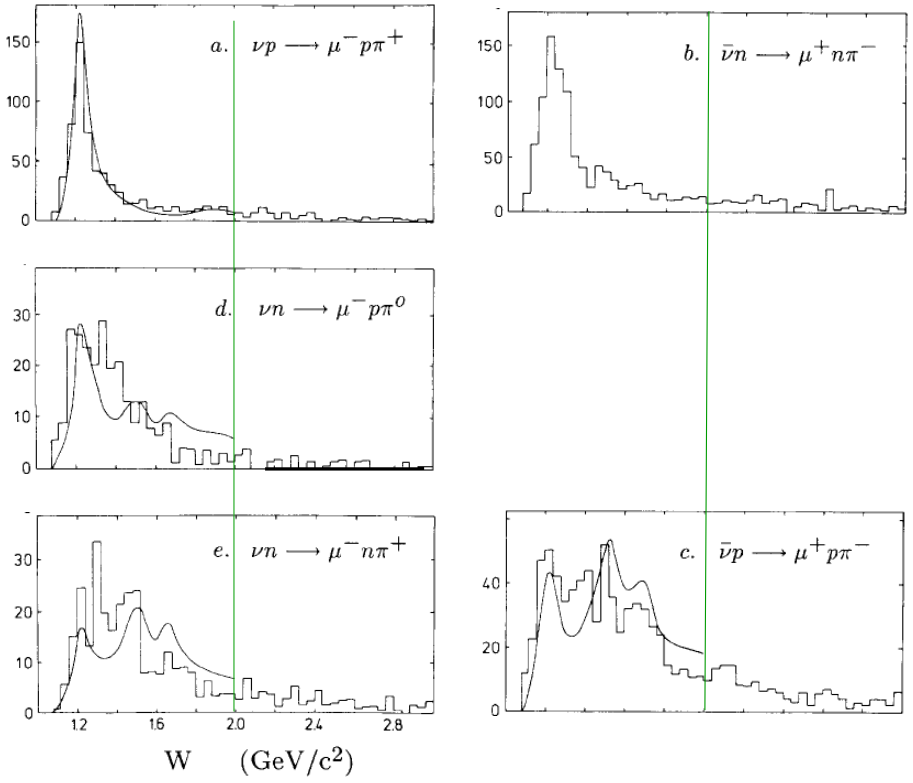
$\bar{\nu}_\mu + p \to \mu^+ + \pi^0 + n$



- Importance of Axial vector coupling :$\Delta(1232)$
- $\sigma_\nu - \sigma_{\bar{\nu}}$ due to A-V interference

$E_\nu = 40GeV(W < 2GeV, Q^2 < 2GeV^2)$





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- $$\frac{d\sigma}{dE_l d\Omega} = \frac{G_F^2 V_{ud}^2 E_l^2}{2\pi^2}[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2} \pm W_3 \frac{E_\nu + E_l}{m_N}\sin^2\frac{\theta}{2}]$$
- Contribution V-A interference term($\sigma_\nu \leftrightarrow \sigma_{\bar{\nu}}$) varies depending on neutrino energy.

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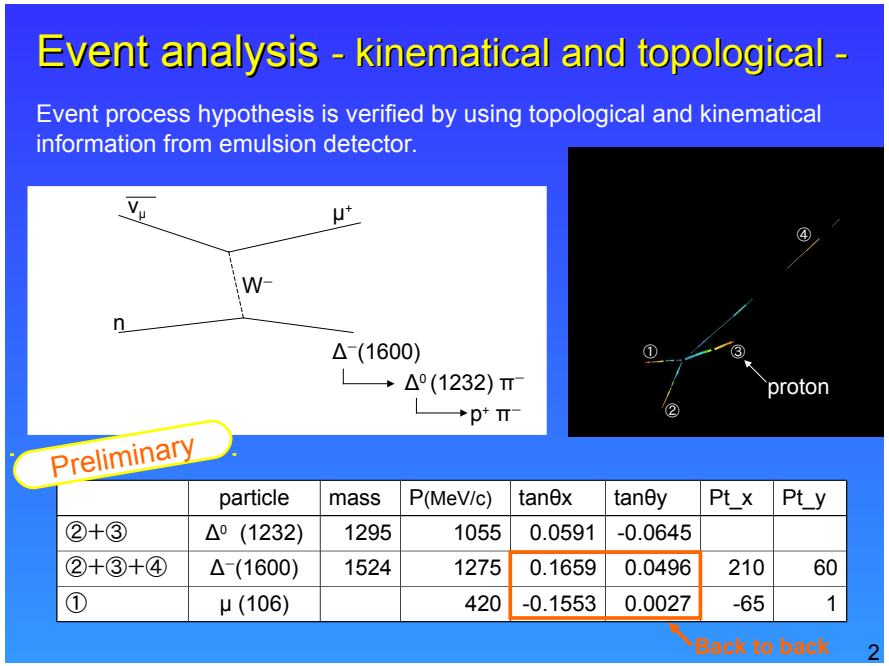
Possibility to study production of N^* or Δ from neutrino reaction



	particle	mass	P(MeV/c)	tanθx	tanθy	Pt_x	Pt_y
②+③	Δ^0 (1232)	1295	1055	0.0591	-0.0645		
②+③+④	Δ^-(1600)	1524	1275	0.1659	0.0496	210	60
①	μ (106)		420	-0.1553	0.0027	-65	1

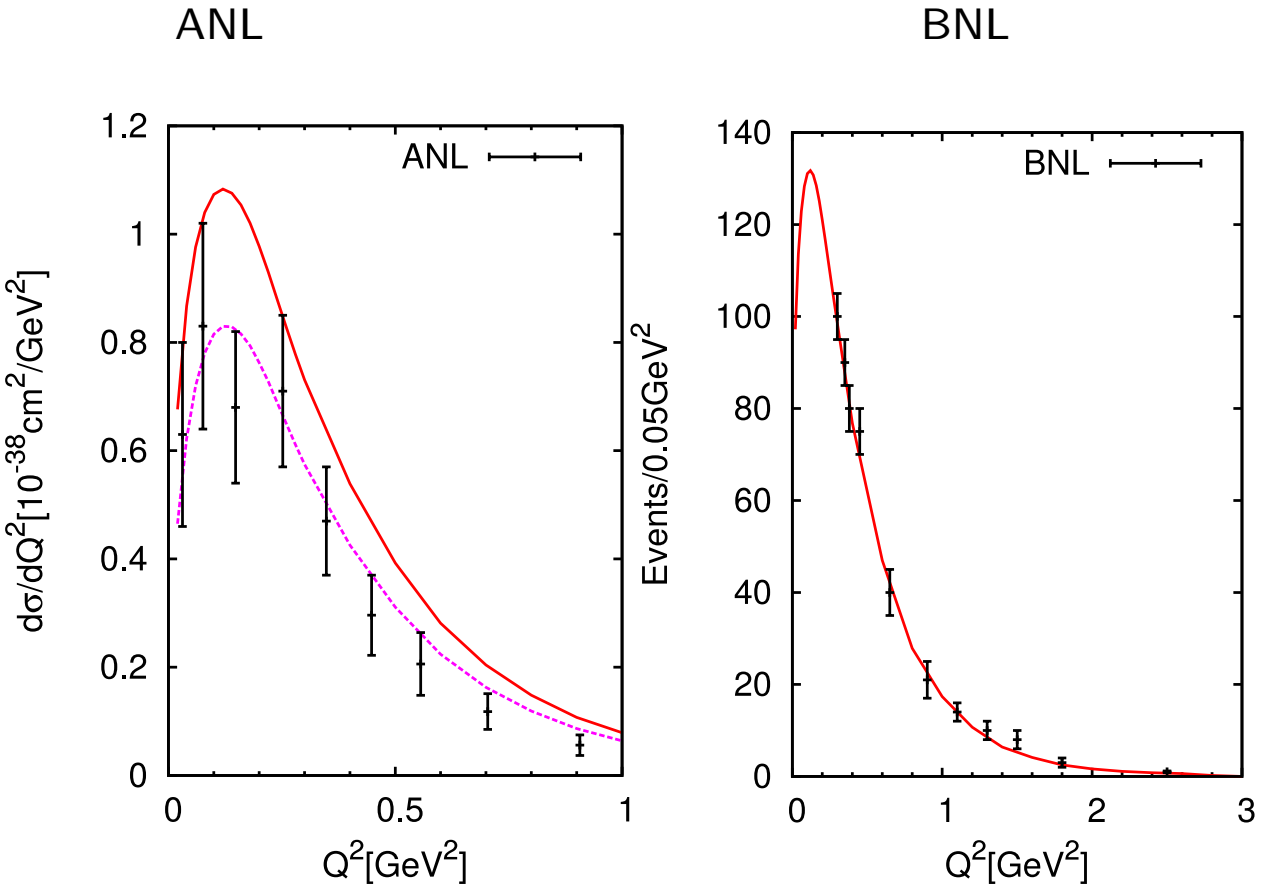
(talk by T. Fukuda at Neutrino Frontier Workshop, Yugawara, Dec. 3, 2015)

Summary

- Current situation of DCC model on neutrino-nucleon reaction in the resonance region is discussed.
- $\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$ coupled channel model for neutrino reaction in resonance region is developed by extending the model for pion and photon induced reactions.
- Both vector and axial-vector responses are equally important for neutrino reaction in the N^* region. In particular, axial vector $N\Delta$ coupling is important, which is the main pion production mechanism for both neutrino and anti-neutrino reaction.
- Some of the reaction models implemented in generator code may be better updated by using models constrained from all available meson production data.
- Note: even GeV neutrino-deuteron reactions, one may need to take account of reaction of multi-nucleon system depending on kinematics.

Q^2 dependence of cross section

(Flux averaged $d\sigma/dQ^2$ for $\nu_\mu + p \to \mu^- + \pi^+ + p$)



Dashed curve: $0.8 \times g_{AN\Delta}(PCAC)$