Neutrino-Nucleus Reaction

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Introduction

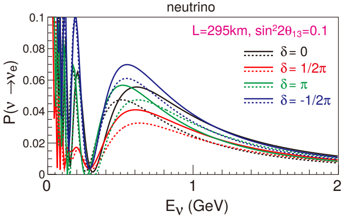
Open Questions on Neutrino Properties

- CP violation in lepton sector
- Mass, Mass hierarchy
- Precise value of mixing angle
- Dirac/Majorana
- ...

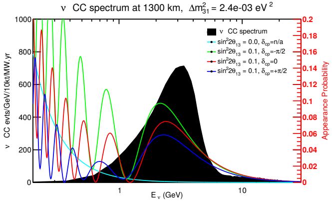
Why neutrino nucleus, nucleon reactions?

Neutrino properties are extracted from neutrino-nucleus reaction in current and future LBL experiment, atmospheric neutrino, reactor neutrino

Precious understanding of neutrino nucleus reaction in the wide energy range is very important to extract neutrino properties from data.



(taken from HK working group arXiv:1412.4673)

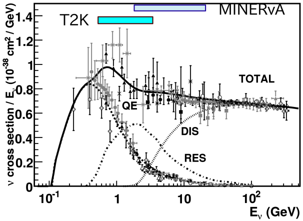


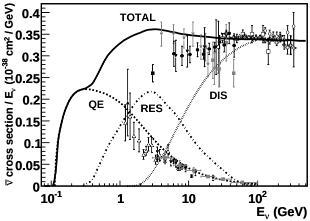
(taken from LBNE collaboration arXiv:1307.7335)

- ν interaction of MeV to GeV
- cross section for ν_e, ν_μ and $\bar{\nu}_e, \bar{\nu}_\mu$ needed

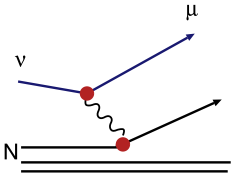
Reaction mechanism

ν $\bar{\nu}$

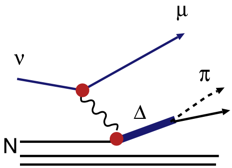




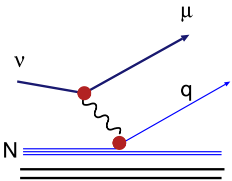
J. A. Formagglo and G. P. Zeller Rev. Mod. Phys. 84 (2012) 1307.



QE



RES



DIS

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

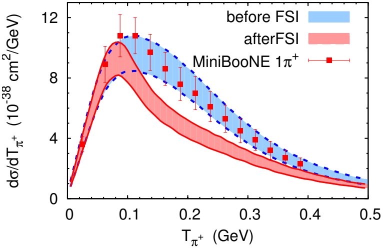
In this talk, 'Neutrino induced meson production reaction' based on

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

Neutrino Induced Pion Production Reactions($\Delta(1232)$)

MiniBooNE data and GiBUU results



(Taken from U. Mosel, arXiv 1602.00696)

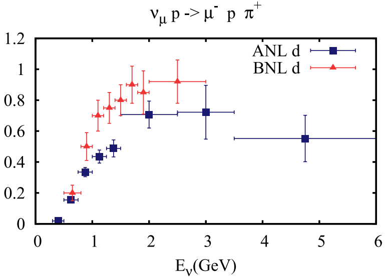
- $\nu - A$ semi-inclusive pion production is not fully understood.
- Ambiguity in the elementary process(ANL/BNL) will be problematic in future higher precision experiments. (M. Wascko 2005, E. Paschos et al. 2004)

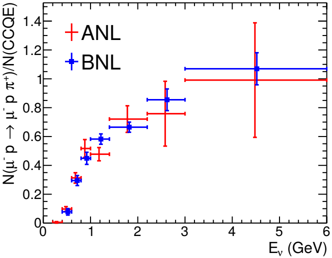
Neutrino induced pion production on nucleon ($W < 1.4$GeV)

- Pion production from $\Delta(1232)$ is main mechanism.
  $\nu_\mu + p \to \mu^- + \pi^+ + p (I = 3/2)$
- Only available data are from ANL(G. Radecky et al. PRD25 (82)), BNL(T. Kitagaki et al. PRD34 (86))

- Solution for ANL/BNL controversy (C. Wilkinson et al. PRD90 (14))
- Caution on FSI for deuteron data(ANL,BNL)(Jia-jun Wu et al. PRC91 (15))

Re-analysis of Bubble chamber data on $\nu_\nu + p \to \mu^- + \pi^+ + p$
C. Wilkinson et al. PRD90 (2014)





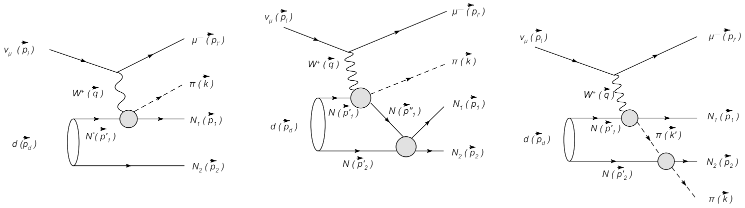
BNL/ANL $\sim$ 1.4 around $E_\nu = 1$GeV

data(pi)/data(non-pi)

- Possible problem of flux normalization $\sigma(E_\nu)\Phi(E_\nu)$
  (pointed out by K. Gaczyk et al PRD80(2009),PRD90(2014))
- Ratios $\sigma(1\pi)/\sigma(0\pi)$ of ANL,BNL experiments are consistent with each other.

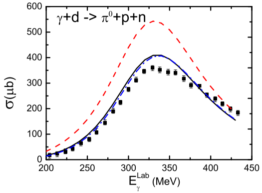
Rescattering effects on $\nu - d$ reaction
Jia-jun Wu et al. PRC91 (2015)

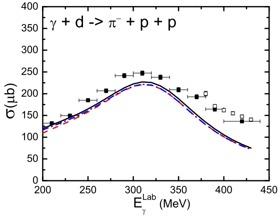
- ANL,BNL data are neutrino reaction on deuteron. No many body effects are taken into account to extract $\nu - N$ cross section.
- rescattering effects are known to be important for $d(\gamma, \pi)NN$



Estimation of rescattering effects:
Dynamical model for $\pi N, (\gamma, \pi), p(e, e'\pi)N$ and $N(\nu, l\pi)N$ in delta-resonance region.
(Sato,Uno,Lee PPC67(03),Matsui,Sato,Lee PRC72(05))
Bonn NN-potential

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

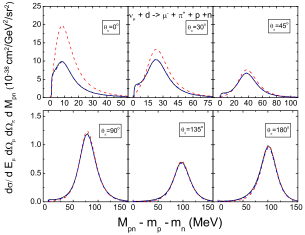


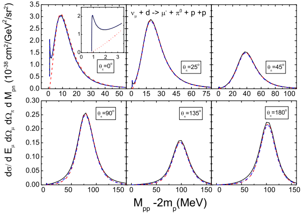


- Large NN rescattering effects for $\gamma + d \to p + n$

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

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

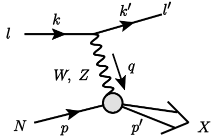




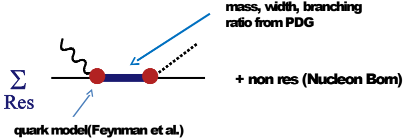
- Large NN rescattering effects for pn final state not pp.
- Low energy pn state $({}^3S_1 - {}^3 D_1)$ must be orthogonal to d.

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

Model of electroweak meson production



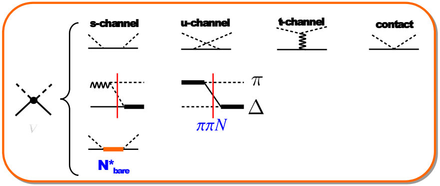
- Rein-Sehgal Ann. Phys. 133 (80), Z. Phys (87): used in generators NEUT, GENIE



- Isobar model
    - 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 model($\pi - N, \gamma - N, e - N$ reactions)
    - Δ region,pion production: Sato,Uno,Lee PPC67(03),Matsui,Sato,Lee PRC72(05)
    - $N*$ region,$\pi, \eta, K, \pi\pi$ productions:Nakamura,Kamano,Sato PRD92(15)

Brief explanation of Coupled-channel model($\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$)

Start from interaction for meson-baryon channel



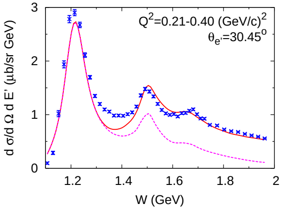
then solve Lippmann-Schwinger Equation.

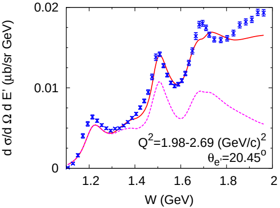
$$T = V + VG_0T$$

- Based on dynamical coupled channel model for pion and photon induced reactions. Kamano, Nakamura, Lee, Sato PRC88(13)
- Vector current: Q^2 ($p(e,e'\pi)$), iso-vector/iso-scalar (γn)
  Axial vector current: $g_A^{NN^*}$ from $g_\pi^{NN^*}$ assuming PCAC
- DCC model is constrained from all available meson production data.

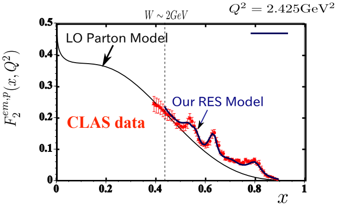
Result of DCC model for $p(e, e'X)$

Inclusive cross section(dotted: single pion production, cross SLAC data)



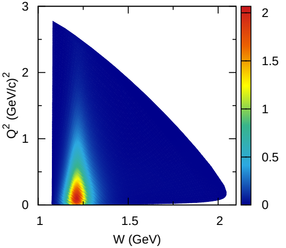


Structure function: compare with parton model:

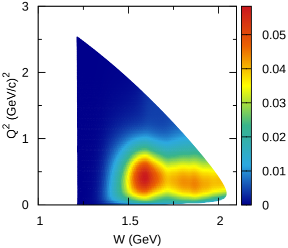


Overview of neutrino induced reaction (DCC model) $E_\nu = 2GeV$

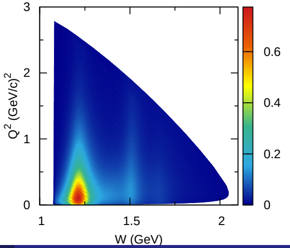
$$\nu_\mu + p \to \mu^- + \pi^+ + p$$



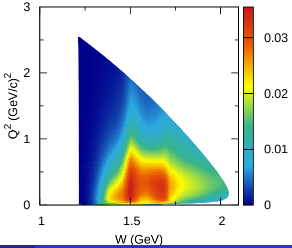
$$\nu_\mu + p \to \mu^- + \pi^+ + \pi^0 + p$$



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



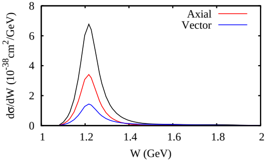
$$\nu_\mu + n \to \mu^- + \pi^+ + \pi^- + p$$



Single pion production at $E_\nu = 2GeV$ ($d\sigma/dW = \int dQ^2 d\sigma/dW/dQ^2$)

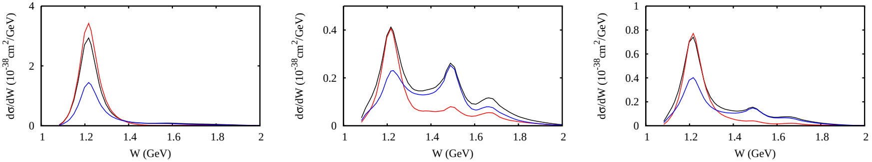
Neutrino reaction

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



Anti-neutrino reaction

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

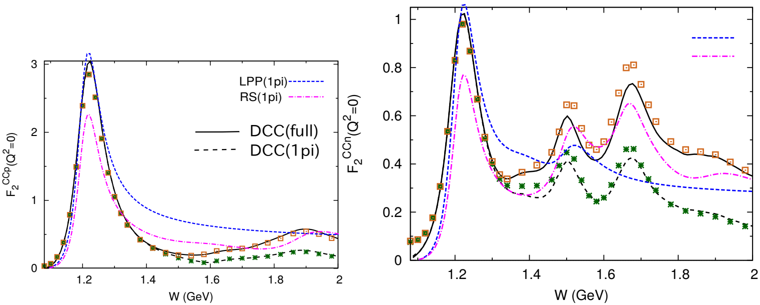


- Importance of Axial vector coupling :$\Delta(1232)$
- $\sigma_\nu - \sigma_{\bar{\nu}}$ due to A-V interference

Total cross section for forward lepton

Assume PCAC ($Q^2 = 0, m_l = 0$)

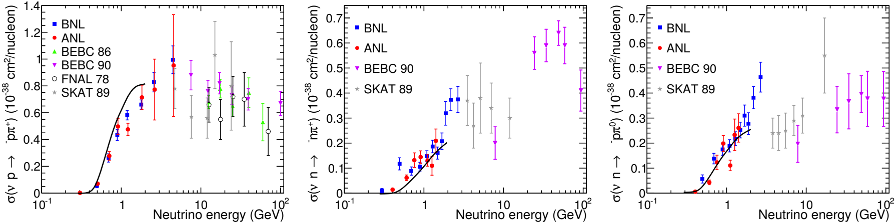
$$\frac{d\sigma^{CC}}{dE_l d\Omega_l} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{E'^2}{E - E'} F_2, \qquad F_2 = \frac{2f_\pi^2}{\pi} \sigma_{tot}(virtual\pi + N)$$



- DCC model: agree with cross section estimated from πN amplitude
- RS and LPP model may overestimate single pion production cross section.

confront with data

Single pion production



DCC model (Solid curve)

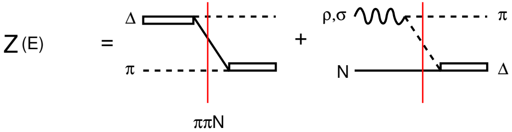
Recent data by Rodrigues et al. arXiv:1601.01888 taking into account for flux consideration of ANL,BNL data

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

Summary

- Current situation of models 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 are better updated by models constrained from all available meson production data.
- Even GeV neutrino-deuteron reactions, one may need to take account of reaction of multi-nucleon system depending on kinematics.

Z-diagram ($\pi\pi N$)



'Singularity'(log) of Z-diagram