Incoherent Pion Production Reaction in Neutrino-Deuteron Reactions

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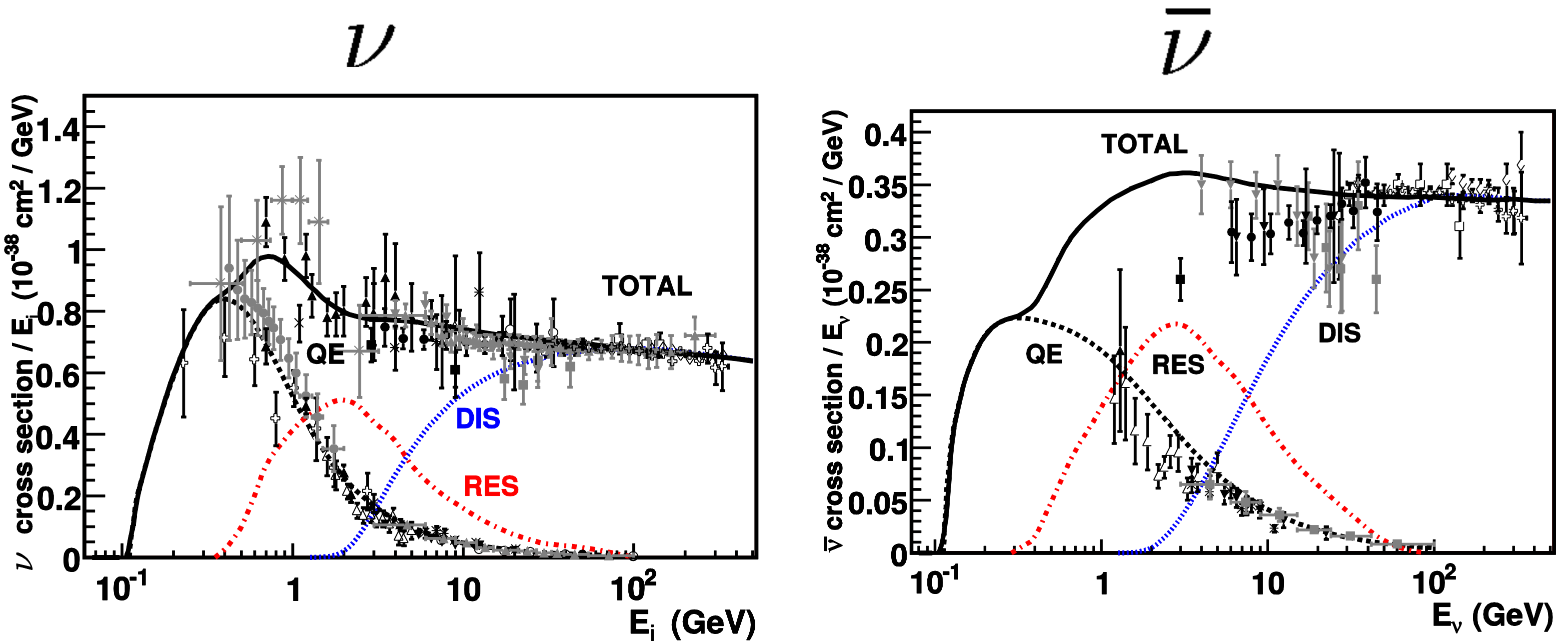
Neutrino-nucleus scattering and LBL neutrino-experiments



$$\sigma_{Tot}/E_{\nu}$$

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

Neutrino energy ~ 0.7GeV (T2K)

Pion production through RES is important process next to QE

Neutrino-nucleon single pion production (Charged current)

Iso-spin decomposition of transition amplitude

$$\left\{\begin{array}{lll} \nu + p & \rightarrow & l^- + \pi^+ + p \\ \nu + n & \rightarrow & l^- + \pi^0 + p \\ \nu + n & \rightarrow & l^- + \pi^+ + n \end{array}\right.$$

$$-\sqrt{2}j^{3/2}$$

$$-\frac{\sqrt{2}}{3}(j^{3/2} + 2j^{1/2})$$

$$-\frac{2}{3}(j^{3/2} - j^{1/2})$$

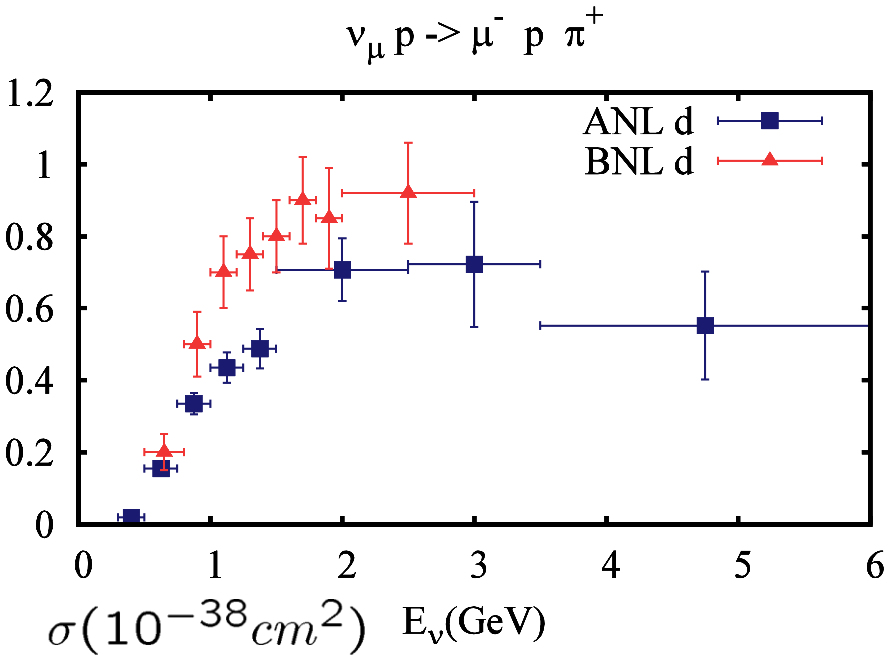
$$\left\{\begin{array}{lll} \bar{\nu} + n & \rightarrow & l^+ + \pi^- + n \\ \bar{\nu} + p & \rightarrow & l^+ + \pi^0 + n \\ \bar{\nu} + p & \rightarrow & l^+ + \pi^- + p \end{array}\right.$$

Excitation of $\Delta_{33}(1232)$ resonance is main pion production mechanism around 1GeV neutrino

Data on single pion production on p or deuteron

ANL G. Radecky et a.l PRD25, 1161 (1982) d (2% p)
BNL T. Kitagaki et al. PRD34, 2554 (1986) d
PRD42, 1331(1990) d

BEBC P. Allen et al. NPB176, 269(1980) H
P. Allen et al. NPB264, 221(1986) H
D.Allasia et al. NPB343, 285(1990) d



Total cross section on pi+ prodproton

BNL/ANL ~ 1.4 around 1GeV

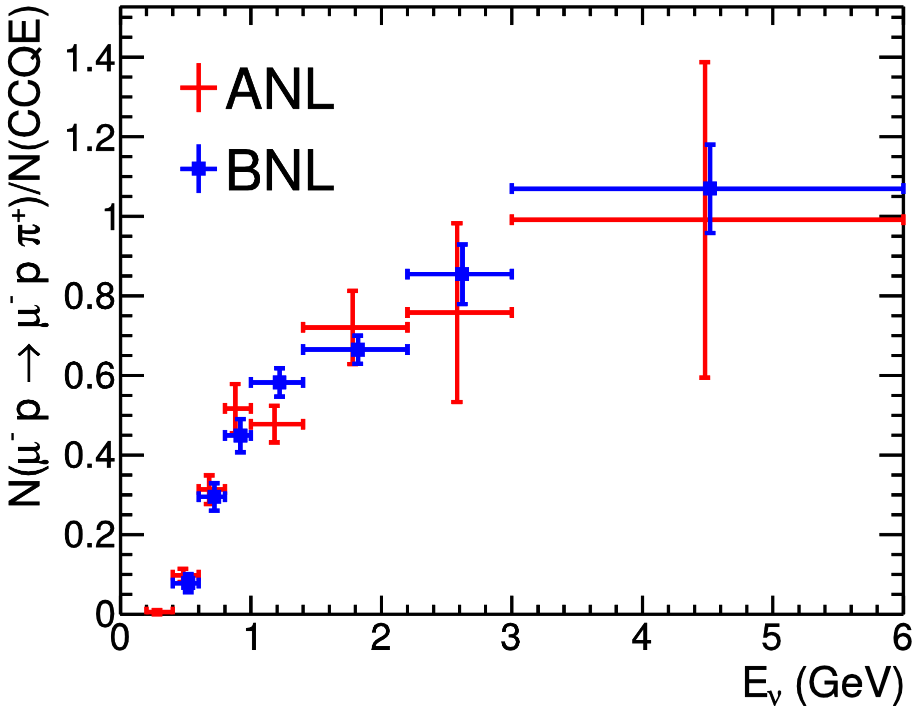
(M. Wascko 2005, E.Paschos et al. 2004)

Data from deuteron reaction

Re-analysis of bubble chamber measurements of muon neutrino induced single pion production

C. Wilkinson, P. Rodrigues, S. Cartwrite, L. Thompson, K. McFarland,
Phys. Rev. D90, 112017 (2014)

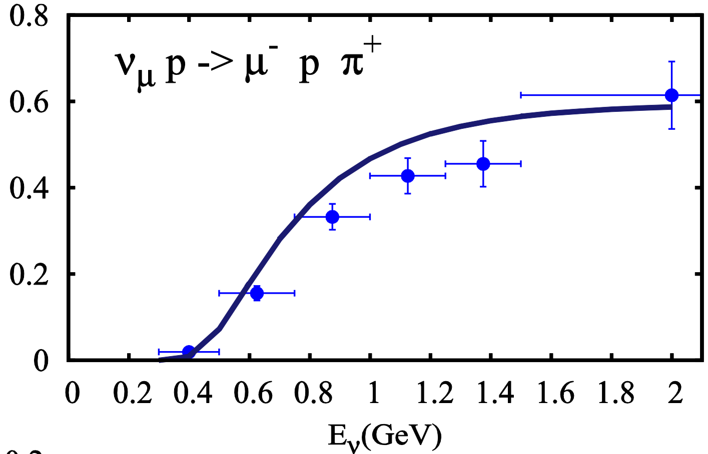
$$N_X(E) = \sigma_X(E)\Phi(E)$$



If one takes ratio of ppi+/CCQE of each data,

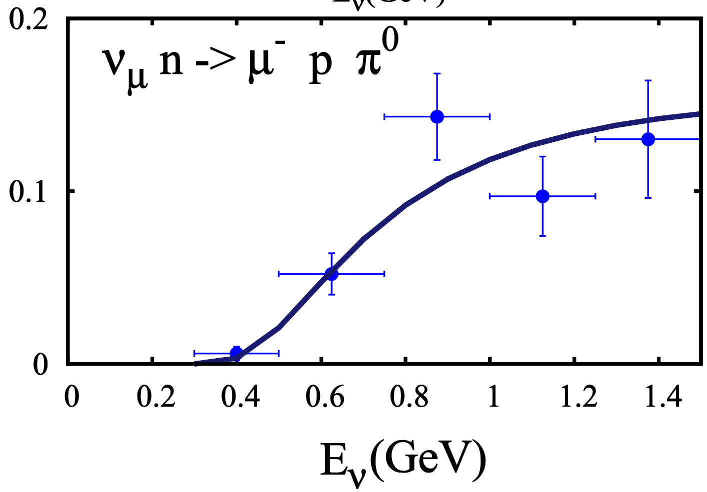
ANL-BNL data are consistent

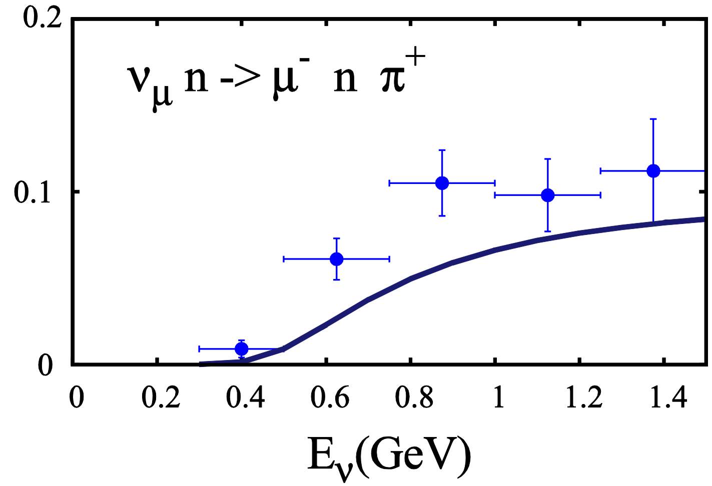
single pion production (three channels) and theoretical model (SL-model)



$\sigma(10^{-38}cm^2)$

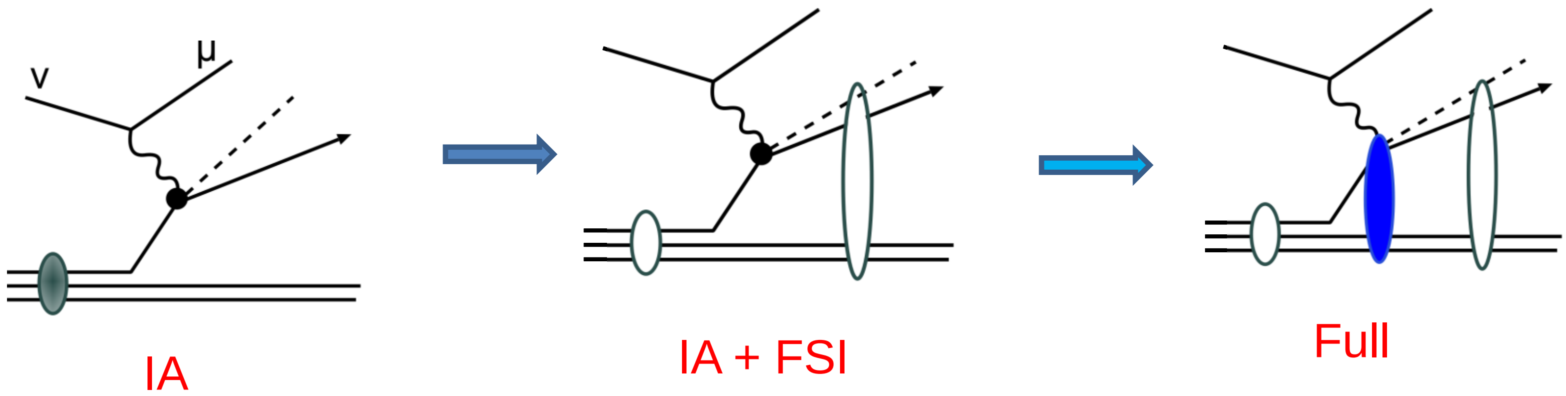
Compare with G. Radecky et al.(ANL)





- data of three channels cannot be explained by assuming Delta(1232) dominance
- SL model is not able to explain all three channels accurately

How important nuclear effects ?



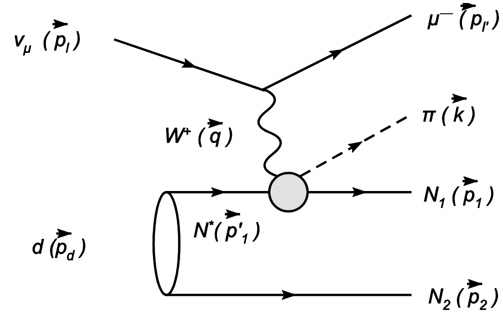
- Previous works on nuclear effects on neutrino-deuteron reaction
  Fermi-Motion L. Alvarez-Ruso et al. PRD59,3386
- Initial state interaction can be well controlled by using realistic deuteron wave function
- Final State Interaction (nucleon-nucleon, pion-nucleon rescattering)
  not yet considered for neutrino reaction
  NN FSI is important for photo-pion production

- Purpose of this analysis

✓ microscopic theoretical estimation of FSI is possible for deuteron
✓ reaction model can be tested by comparing data of pion photoproduction
✓ predict nuclear effects on neutrino reaction

Impulse amplitude

Fermi motion is included

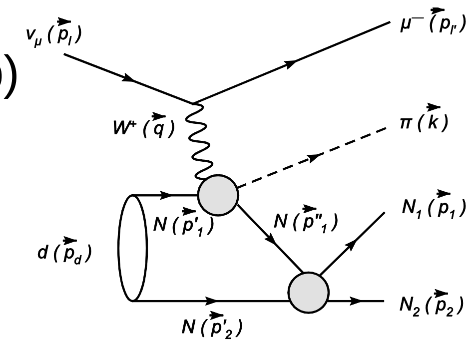


$$< \Psi_{NN} | T_{\gamma\pi} | \Psi_d >$$

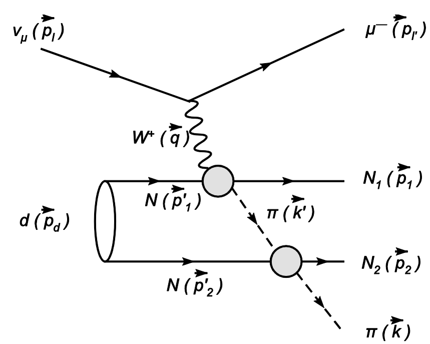
~ DWIA

Final state interaction(one-loop)

Nucleon-nucleon scattering



Pion-N rescattering



FSI in pion photoproduction

J.M. Laget Phys.Rep 69,1(1981),M.Schwamb Phys.Rep. 485,109(2010)

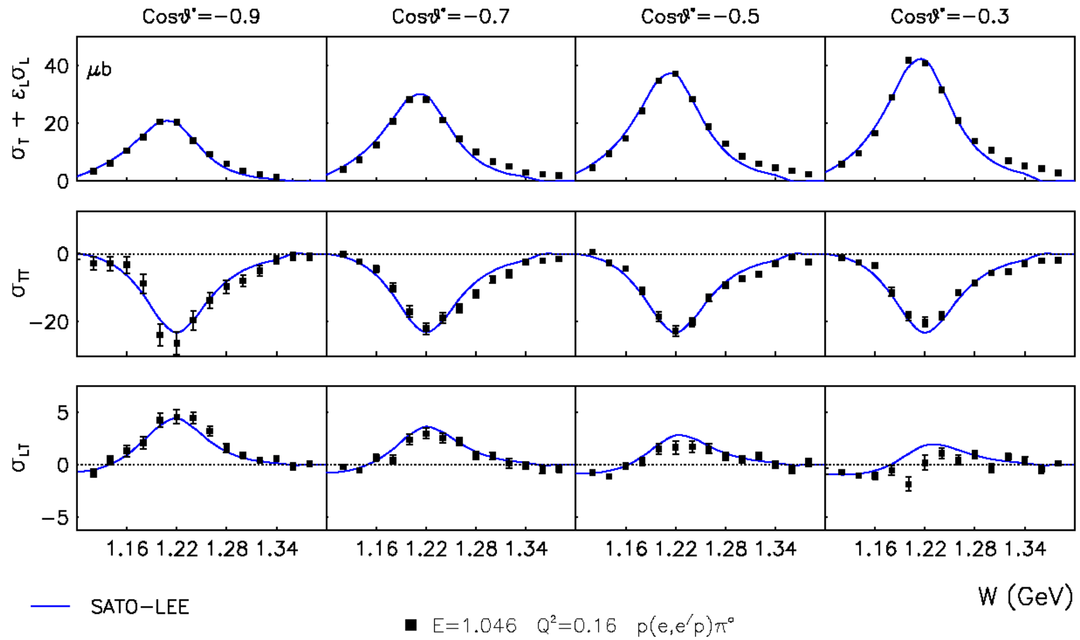
M.I.Levchuk et al., PRC74,014004(2006)

Brief explanation of SL-model

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

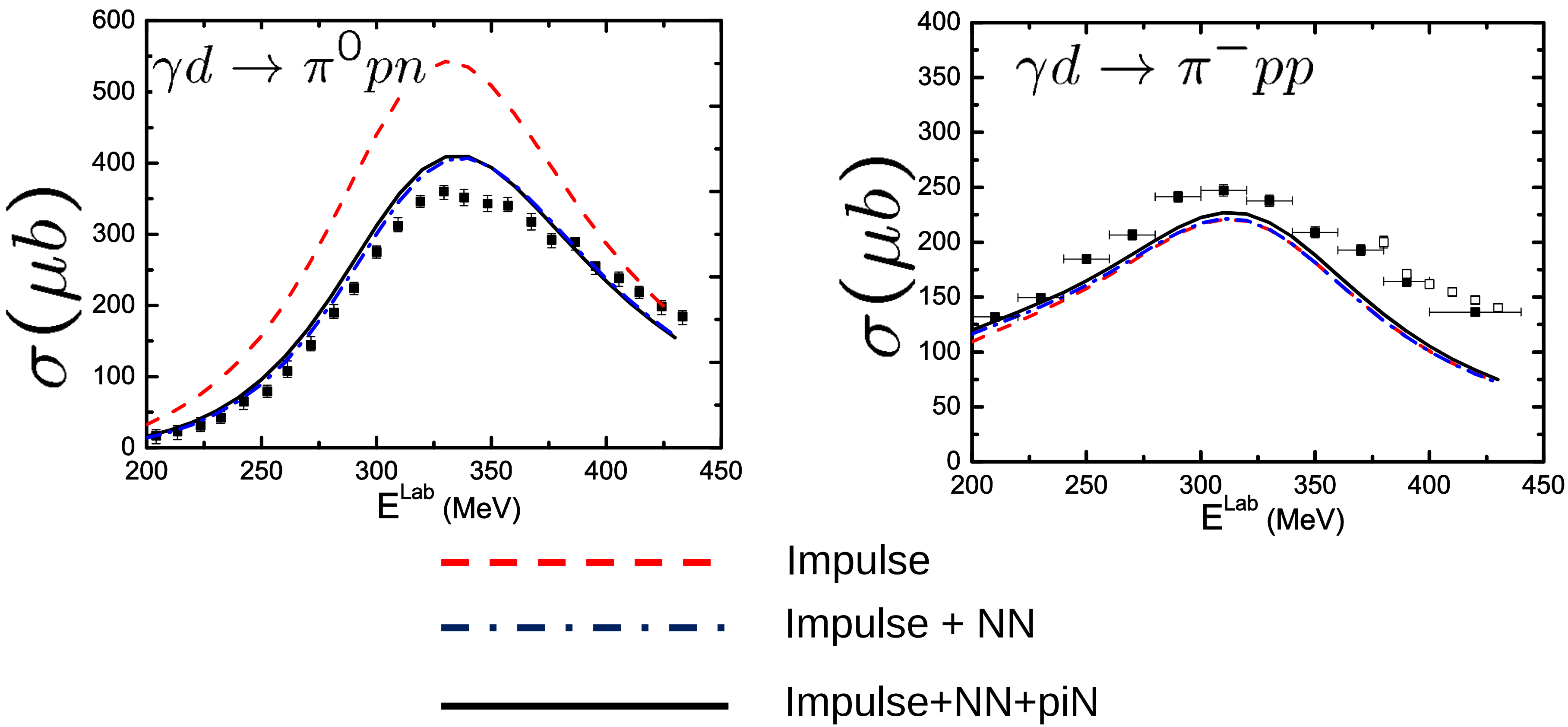
- ✓ Delta resonance + non-resonant mechansim(consistent with chiral Lagrangian)
- ✓ Model for pi-N scattering and electroweak pion production with unitarity
- ✓ pi-N elastic scattering: determine most of model parameters of strong interaction
- ✓ pion photo, electroproduction: gamma-N-D coupling constant
- ✓ Weak pion production: assume quark model relation for A-N-D coupling constant

Pion electroproduction Structure functions (CLAS data from C. Smith,2004)



FSI : pion production reaction on deuteron

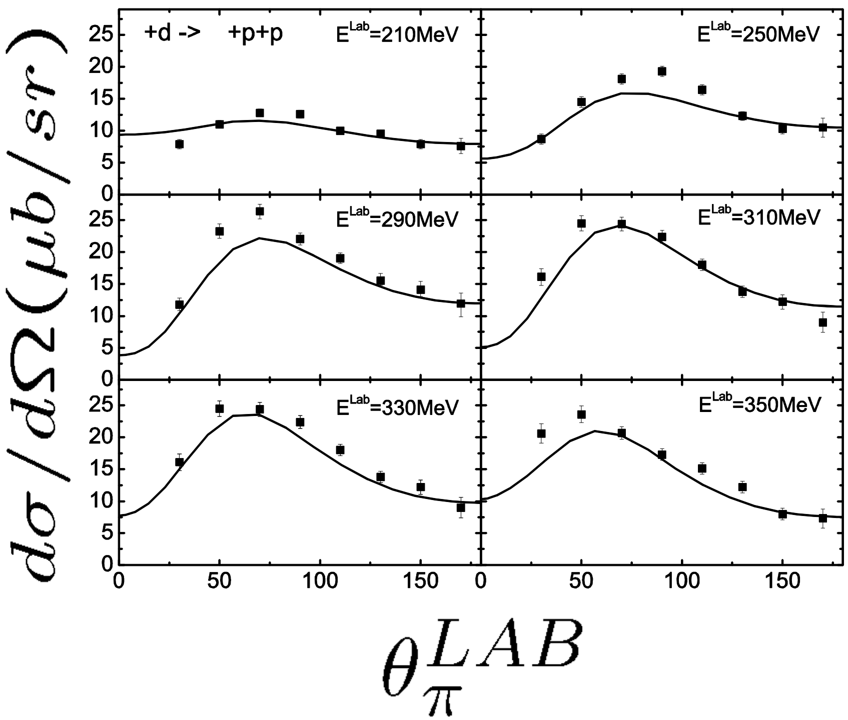
Pion photoproduction(Total cross section) and role of FSI



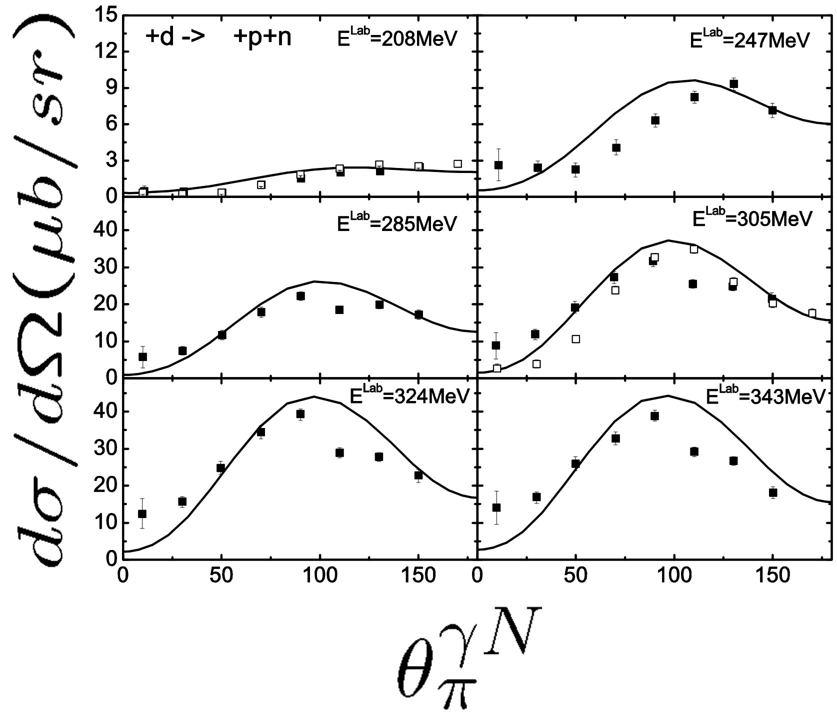
Large FSI(NN) for pi0 production

Pion photoproduction (Differential cross section)

$$\gamma d \to \pi^- pp$$



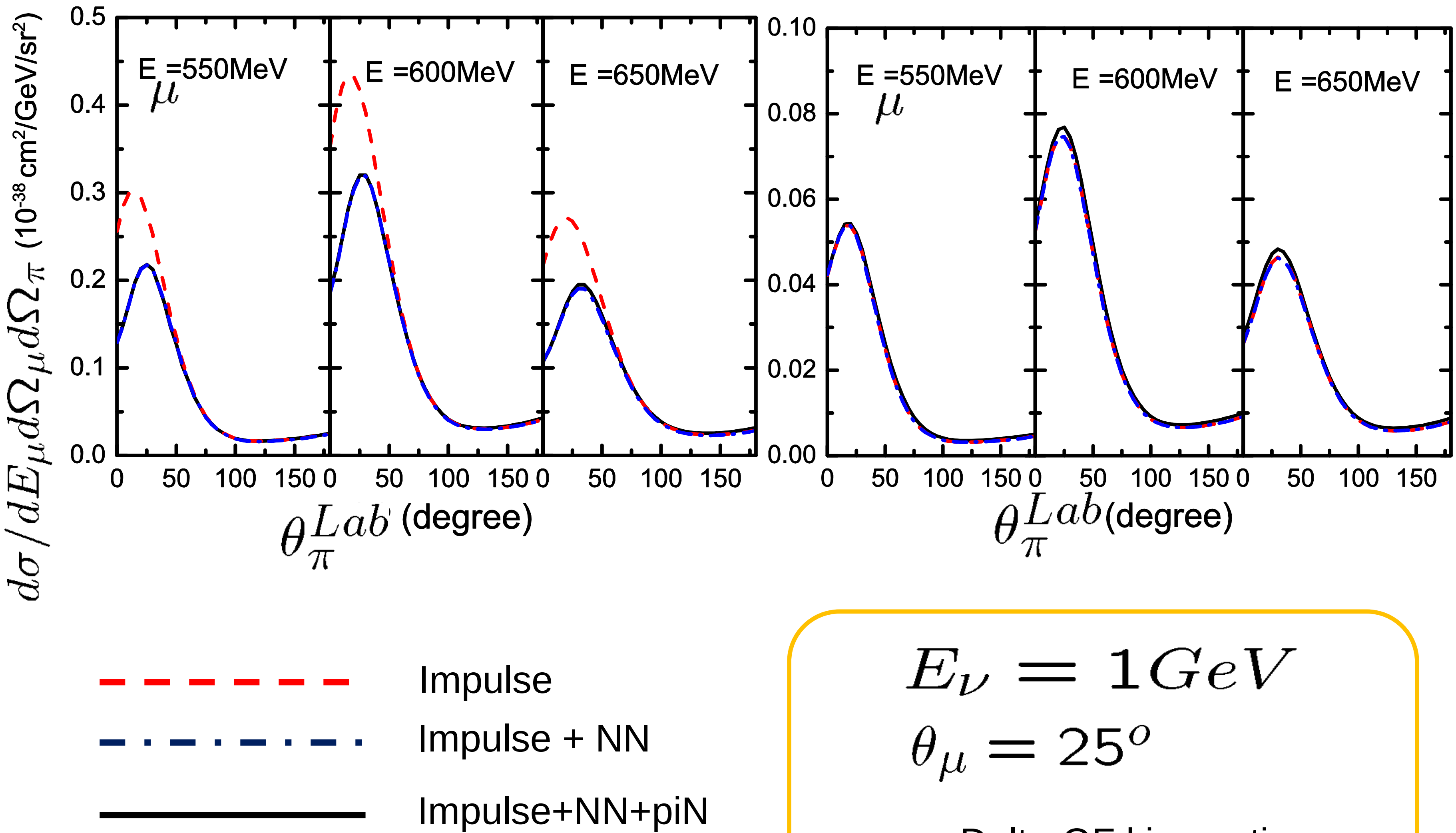
$$\gamma d \to \pi^0 pn$$



With FSI, both pi- and pi0 production angular distribution is well reproduced.

neutrino breakup of deuteron

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

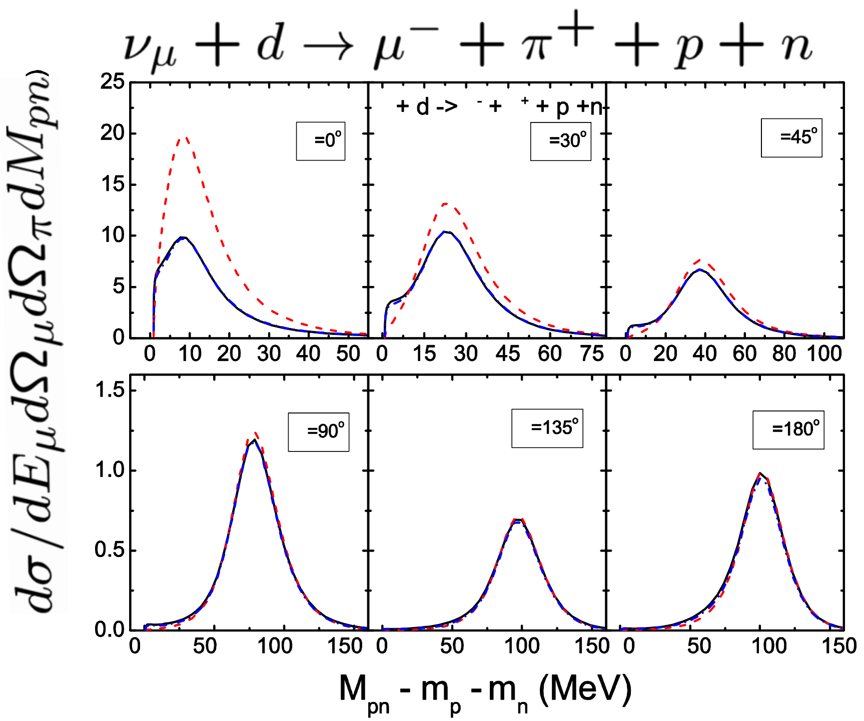


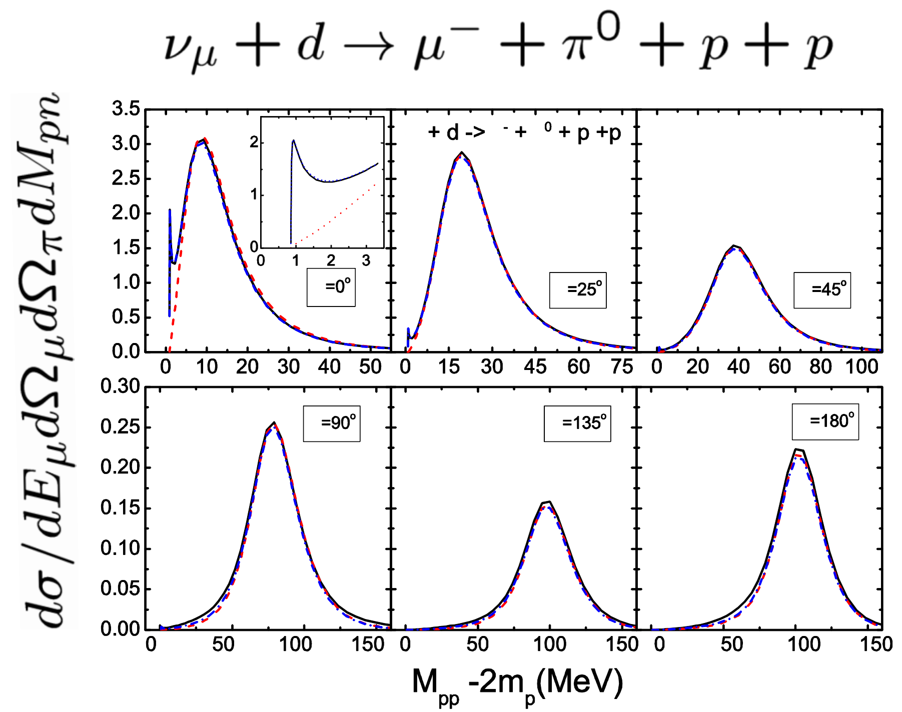
$E_\nu = 1 GeV$

$\theta_\mu = 25^o$

~ Delta-QF kinematics

pn invariant mass distribution





NN FSI for s-wave has large effects for forward pion production

Summary

- 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:

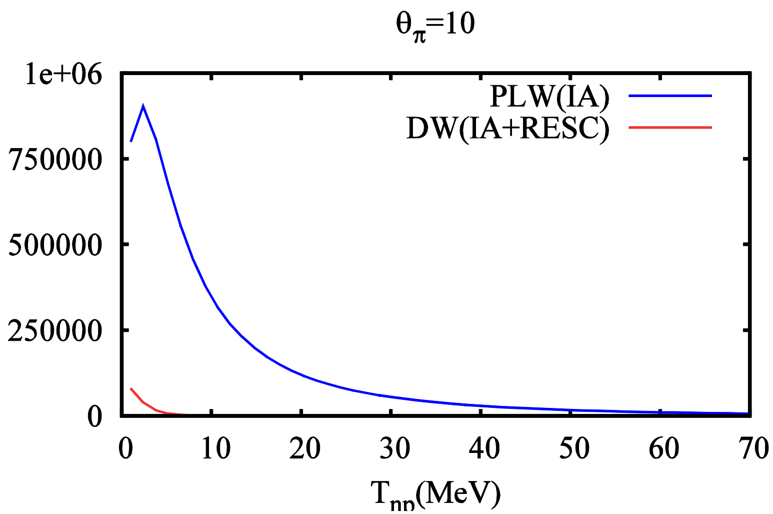
Large effects of nucleon rescattering even Delta-QE peak especially FSI in 3S1 >1S0

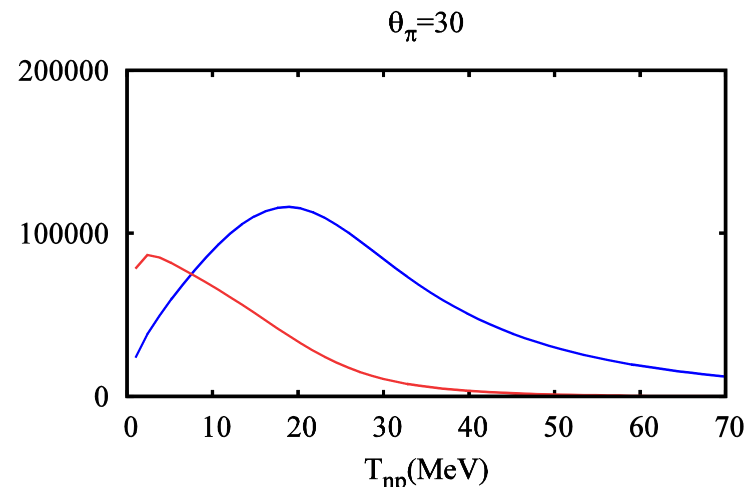
Effects of piN rescattering were small

$$d\sigma \sim |\int \Psi_{scatt}(r) j_0(|\vec{q}-\vec{p}_\pi|/2r)\Psi_d(r) r^2 dr|^2 p_N N p_\pi^2$$

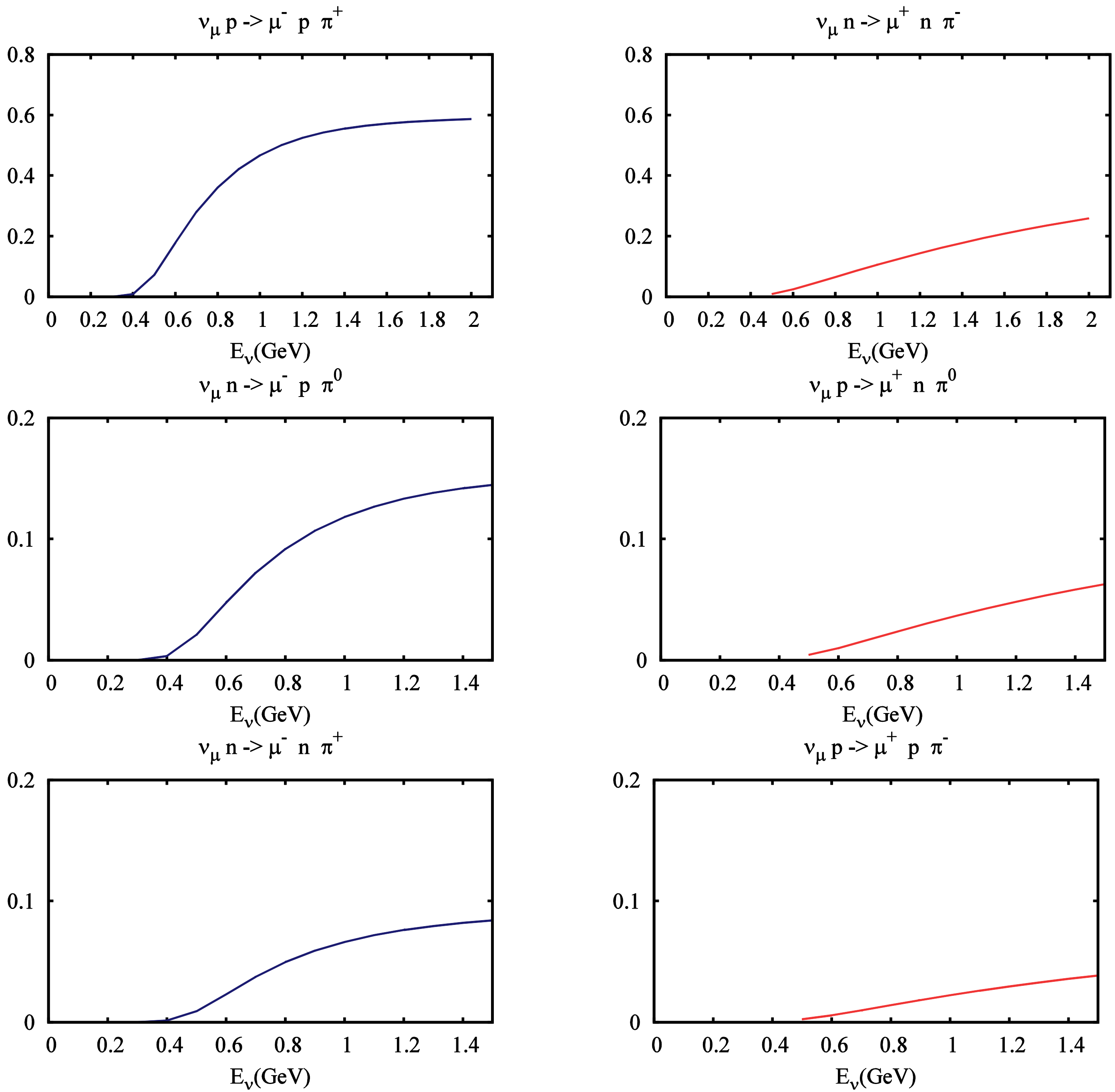
$$^3S_1(d) \to ^3S_1(T=0), ^1S_0(T=1)$$

pn pn,pp,nn



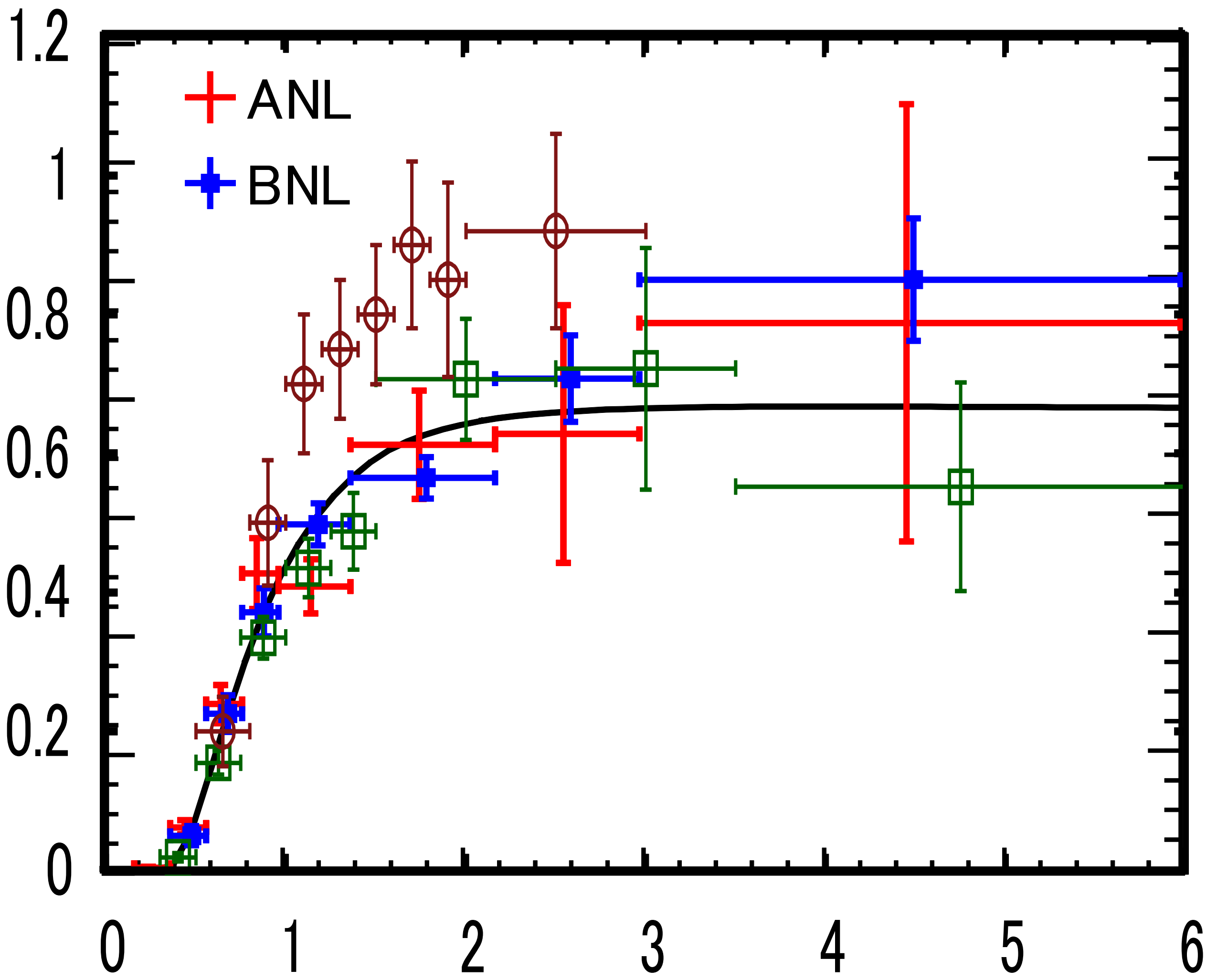


$$d \to ^3S_1(scatt)$$



ν_μ p -> μ^- p π^+
ν_μ n -> μ^+ n π^-
ν_μ n -> μ^- p π^0
ν_μ p -> μ^+ n π^0
ν_μ n -> μ^- n π^+
ν_μ p -> μ^+ p π^-
E_ν(GeV)
0
0.1
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Compare with original ANL and BNL

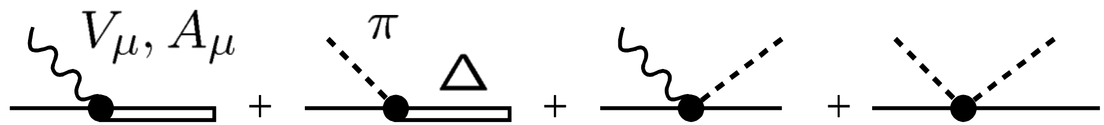


Model of pi-N, electroweak pion production T-matrix for the delta(1232) resonance region (W<1.3GeV, SL model)

Start from Lagrangian based on chiral symmetry and electroweak Standard Model

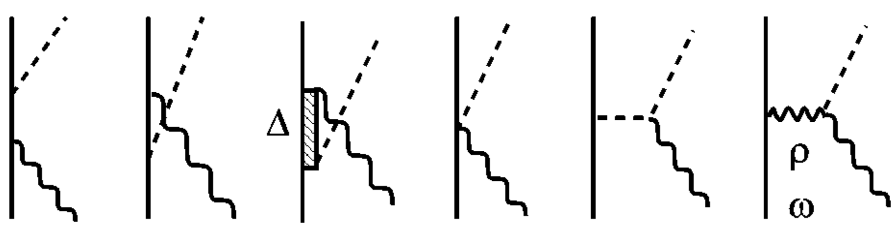
Sato,Uno,Lee PRC67(2003) CC
Matsui,Sato,Lee PRC72(2005) NC, PV(e,e')

Effective Hamiltonian

$H = H_0 +$ 

resonance Non-resonant int.

Vector



Axial vector