NEUT library
used in Super-K and K2K

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Outline

I. Introduction
II. Quasi-elastic scattering
III. Coherent π production
IV. Deep inelastic scattering
V. Nuclear effect

Introduction

NEUT is a neutrino interaction simulation library
used in Super-K, K2K, SciBooNE, and T2K
Originally produced for Kamiokande
several 10s MeV ~ 1TeV is supported

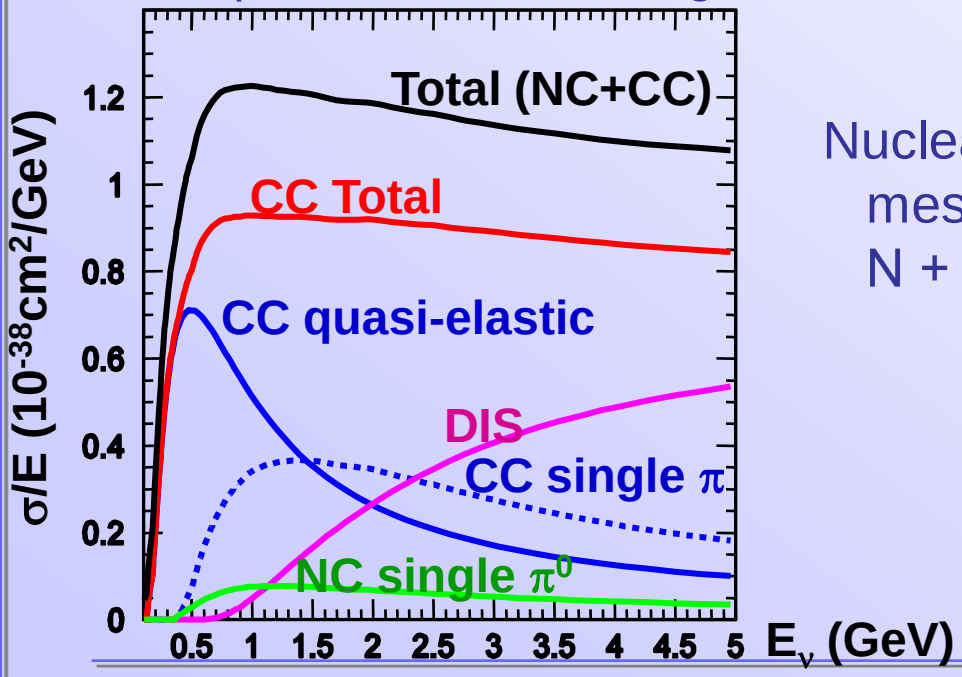
Previously an implementation of NEUT
was presented at NuInt01 by Y.Hayato

In this talk, I present updates from the previous talk
around several GeV

Introduction

Neutrino interaction around 1GeV

- Charged current Quasi-elastic(CCQE) $\nu + n \rightarrow l + p$
- Neutral current elastic $\nu + N \rightarrow \nu + N'$
- Single meson $\nu + N \rightarrow l + N' + \pi(\eta,K)$
- Coherent π $\nu + X \rightarrow l + X' + p$
- Deep inelastic scattering $\nu + q \rightarrow l + q + m\pi(\eta,K)$



Nuclear effects are also taken into account

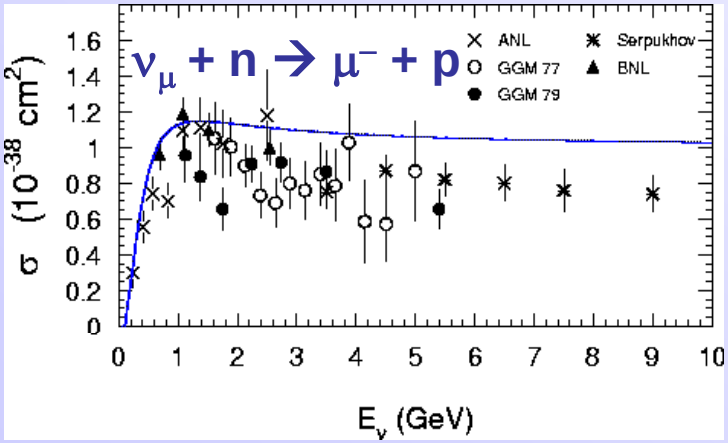
meson(π,K,η,ω) + N → meson' + N'

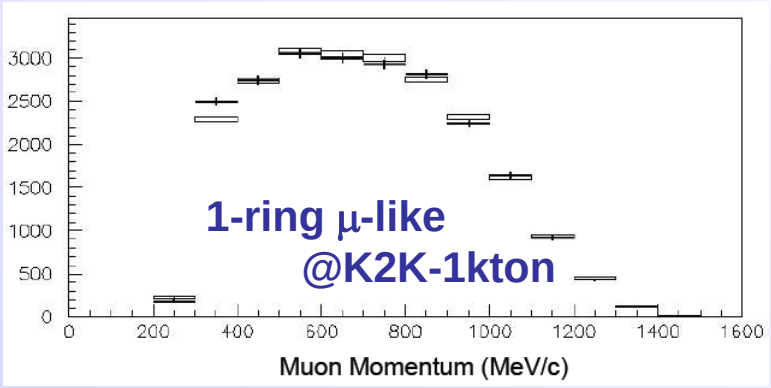
N + N' → N'' + N'''

Quasi-elastic

As for *free nucleon,*
Based on Llewellyn-Smith
Dipole form factor is used ➔ problem of vector FF and M_A

As for *bound nucleon*,
Based on Smith&Moniz



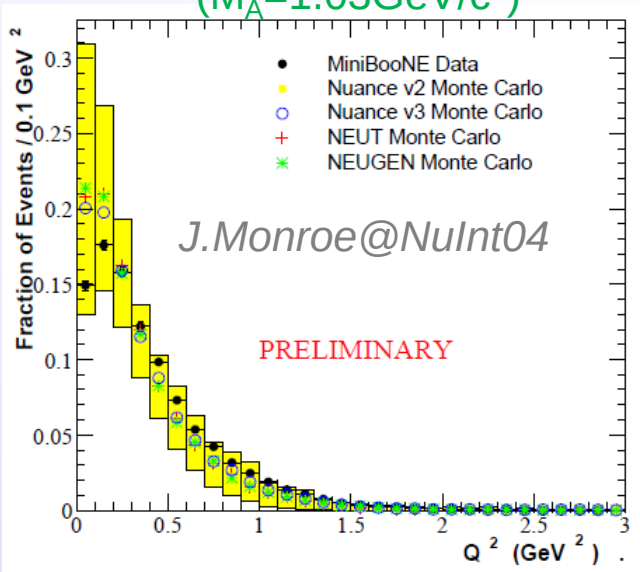


M_A is set to 1.1GeV/c^2 for both QE and 1π
based on K2K analysis(PRL 90, 041801)

Quasi-elastic

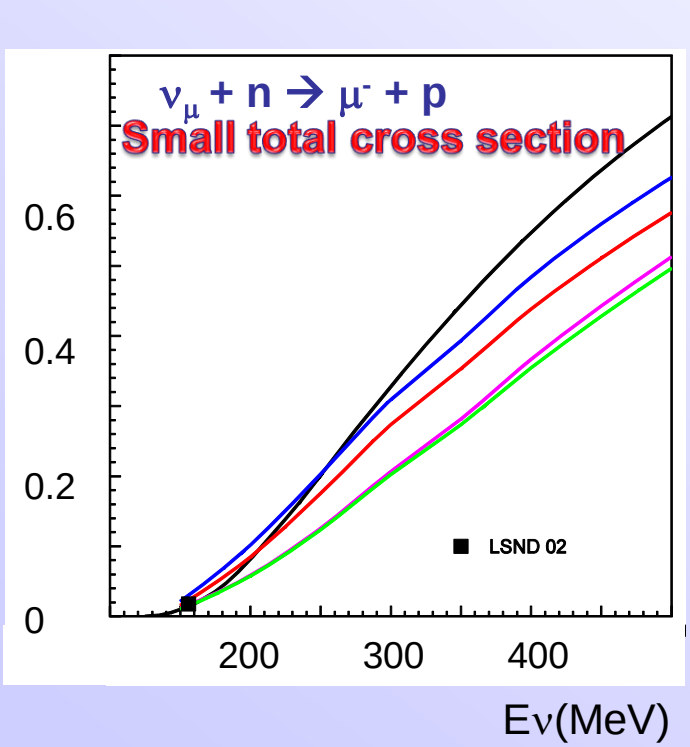
- MiniBooNE reports disagreement between Smith&Moniz and their data in low Q^2 region
  - NUANCE ver.2 & NEUT : Smith&Moniz
  - NUANCE ver.3 : custom π absorption model
  - NUGEN : Bodek&Ritchie modified Fermi gas
- extend to other target besides $^{12}C/^{16}O$
  - → Is Fermi gas too simple ?
- Recently, new improved models are proposed
  - e.g. spectral function
  - (H.Nakamura et al. NuclPhys B Proc.112. 197)
  - or many-body theorem
  - (J.Nieves et al. PRC 70, 055503)
    - SP : does not include FSI, support thr. ~ a few GeV
    - Nieves : includes FSI, support thr. ~ 500MeV, nucleon re-scattering

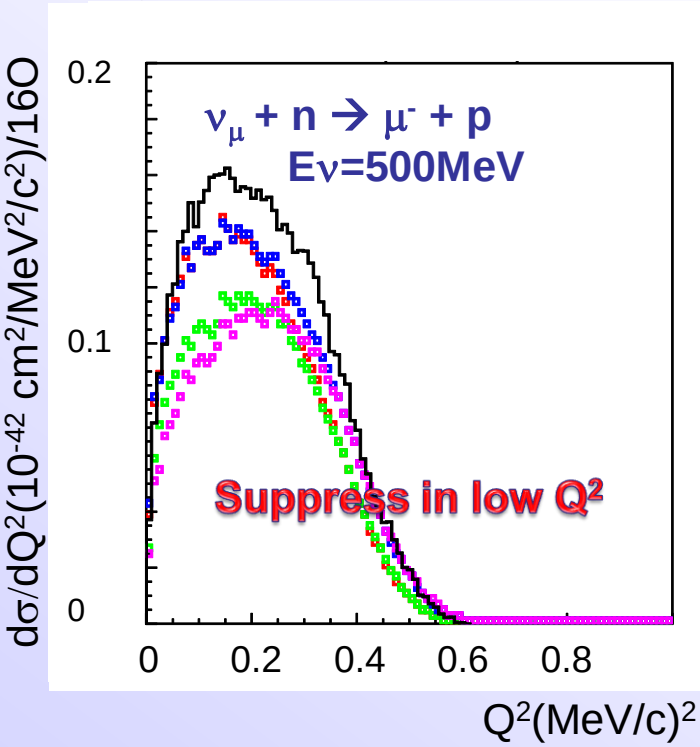
MiniBooNE
(M_A=1.03GeV/c^2)



Quasi-elastic

Now, we are interested in Nieves et al. model
based on many-body theorem and apply RPA and FSI





Black:Smith&Moniz

Nieves et al. model
Blue :null corr.
Red :FSI
Pink :RPA
Green:FSI+RPA

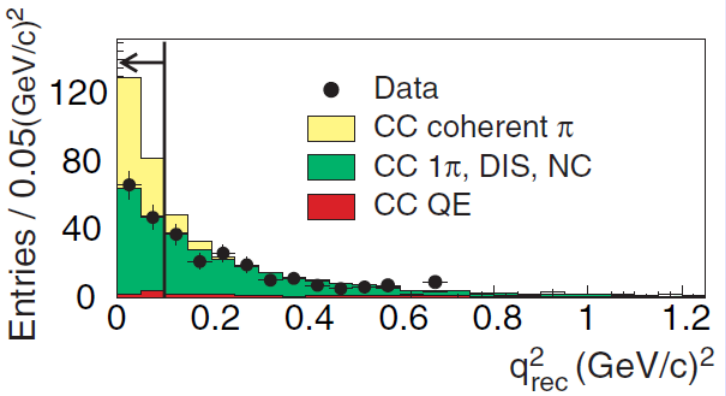
$M_A = 1.1 GeV/c^2$

Can low Q^2 problem be solved by this model ?
Currently, this model is limited to Eν<500MeV
Applicability to higher energy is desirable

Coherent π production

- π^0 from NC coherent π can be a BG for $\nu_\mu \rightarrow \nu_e$ search

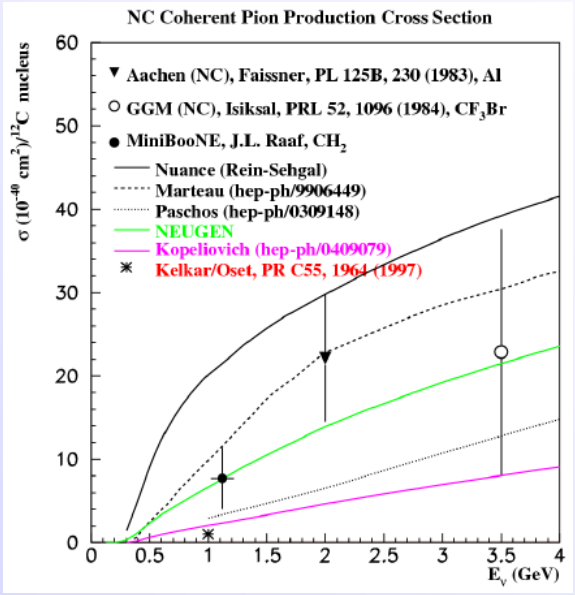
CC is constrained by K2K SciBar detector (PRL 95, 252301 (2005))



➔ σ_{CC}<7.7x10^{-40}cm^2 @<Eν>=1.3GeV

In NC, from MiniBooNE (Fermilab-thesis 2005-20)

➔σ_{NC}~7.7x10^{-40}cm^2 @<Eν>=1.1GeV



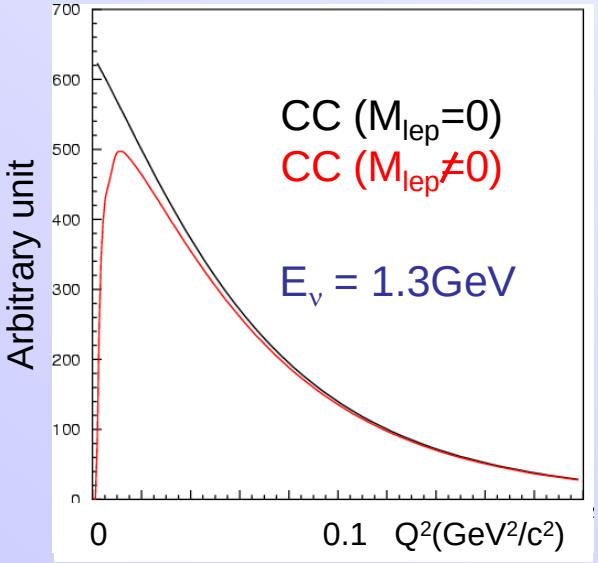
More statistics are necessary for precise analysis

We tried 2 models recently published:

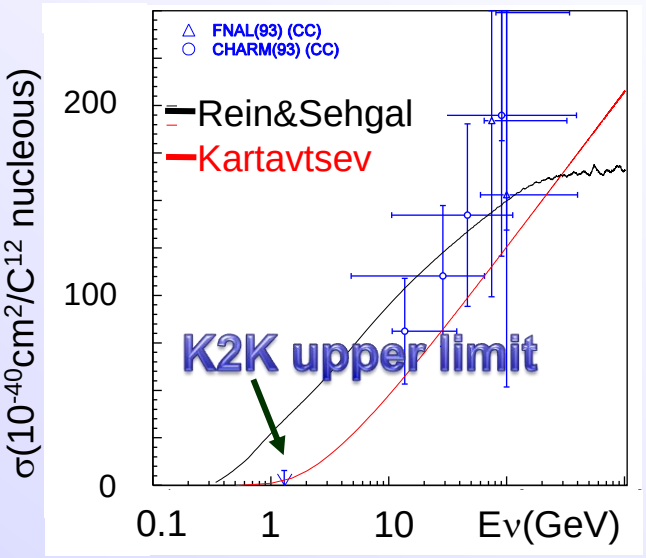
1. Rein&Sehgal w/ lepton mass correction
2. Kartavtsev et al.

Coherent π production

Rein&Sehgal pointed out lepton mass correction was needed for CC process (hep-ph/0606185)



Kartavtsev et al. calculate kinematics without Adler-relation (PRD 74, 054007)



Kinematics can be compared using future data e.g. SciBooNE, MINERvA …

Deep inelastic scattering

Deep inelastic scattering(DIS)
is especially important for atmospheric neutrino analysis

$$\frac{d^2\sigma^\nu}{dxdy} = \frac{G_F^2 m_N E_\nu}{\pi}\left[(1-y+\frac{1}{2}y^2+C_1)F_2(x)+y(1-\frac{1}{2}y+C_2)[xF_3(x)]\right]$$

$$C_1 = \frac{m_\ell^2(y-2)}{4m_N E_\nu x} - \frac{m_N xy}{2E_\nu} - \frac{m_\ell^2}{4E_\nu^2},$$

$$C_2 = -\frac{m_\ell^2}{4m_N E_\nu x},$$

Parton distribution functions(PDF) are used to determine the nucleon structure functions F_2 and xF_3

In NEUT, Kinematics are calculated on two regions

- 1.3GeV<W<2.0GeV → use custom routine to treat PDF
- 2.0GeV<W → use Jetset-7.4(PYTHIA-5.72)

1. W in W<2.0GeV is determined by KNO scaling
2. Mean multiplicity of charged π is determined by
   $\langle n_\pi \rangle = 0.09 + 1.83 \ln W^2$ (J.S.Barish et al. Phys. ReV. D17,1)
3. Forward-backward asymmetry of pion multiplicity(n_π^F/n_π^B) follows
   $$\frac{n_\pi^F}{n_\pi^B} = \frac{0.35 + 0.41 \ln W^2}{0.50 + 0.09 \ln W^2}$$ (S.Barlag et al. Z.Phys. C11, 283)

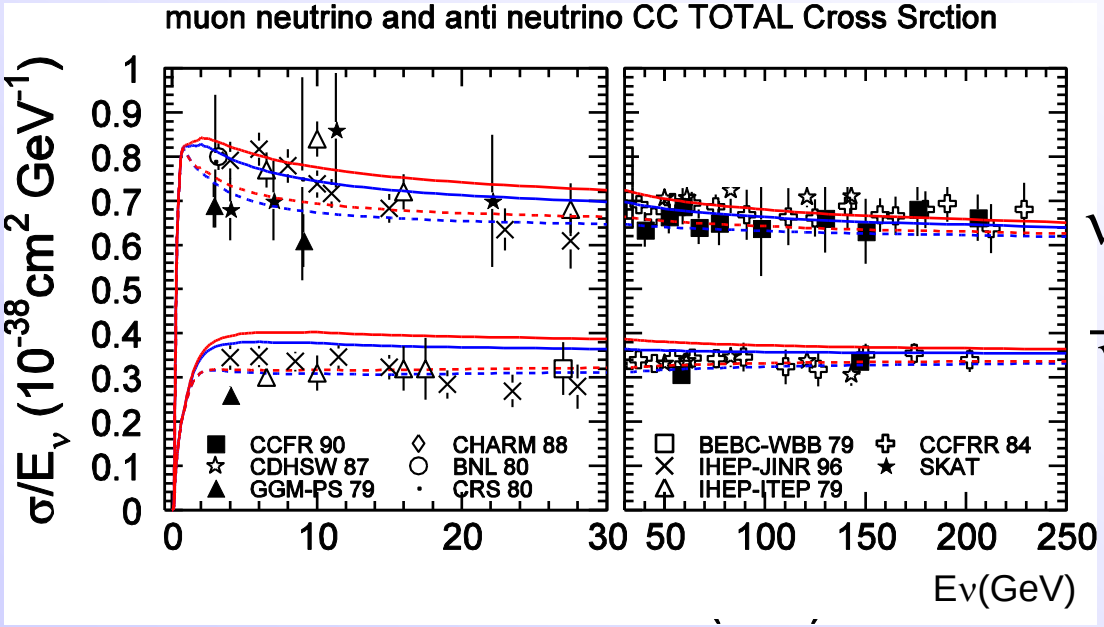
Deep inelastic scattering

Many PDFs are constructed
using higher energy electron/μ/ν scattering and Drell-Yang data

➔ For accelerator neutrino experiments
PDFs with good agreement at lower energy/Q^2 are required

NEUT use GRV94/98 with Bodek&Yang correction
(hep-ex/0203009, hep-ex/0308007)

Deep inelastic scattering

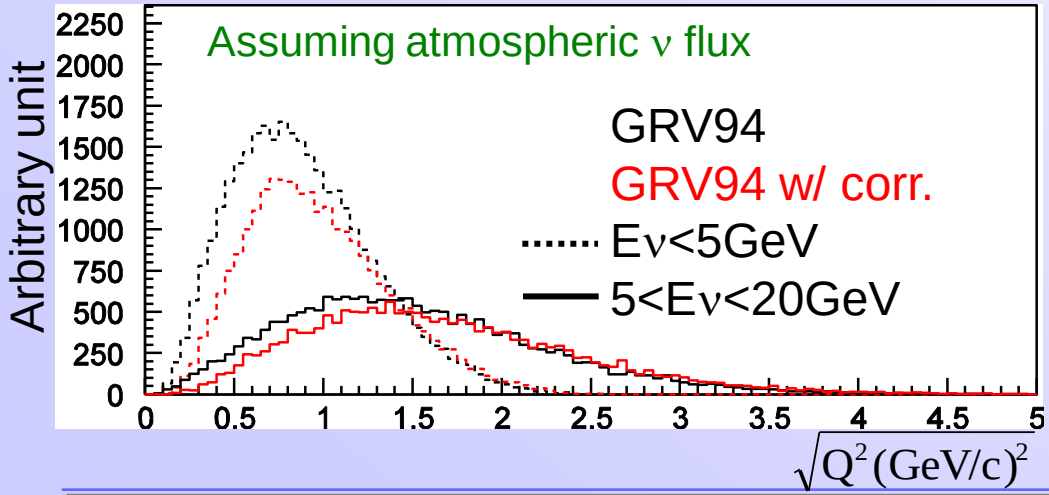


ν_μ

$\overline{\nu}_\mu$

GRV94
GRV94 w/ corr.
GRV98
GRV98 w/ corr.

NOTE:charm correction is not taken into account

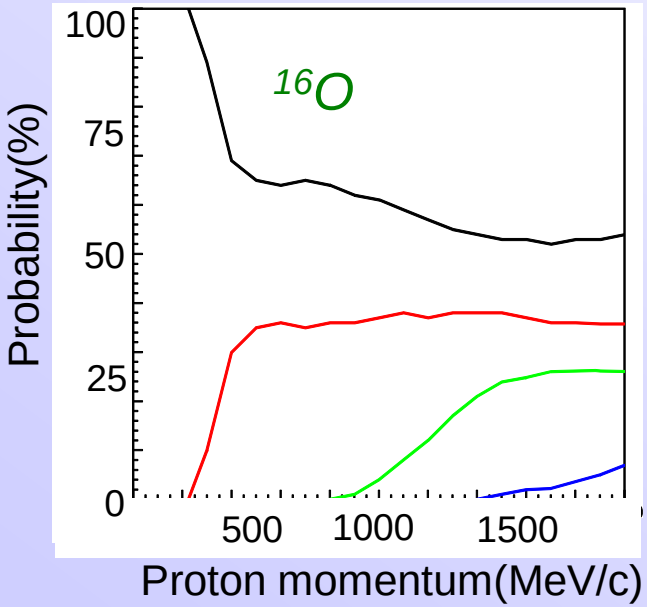


Taking into account
Bodek&Yang correction,

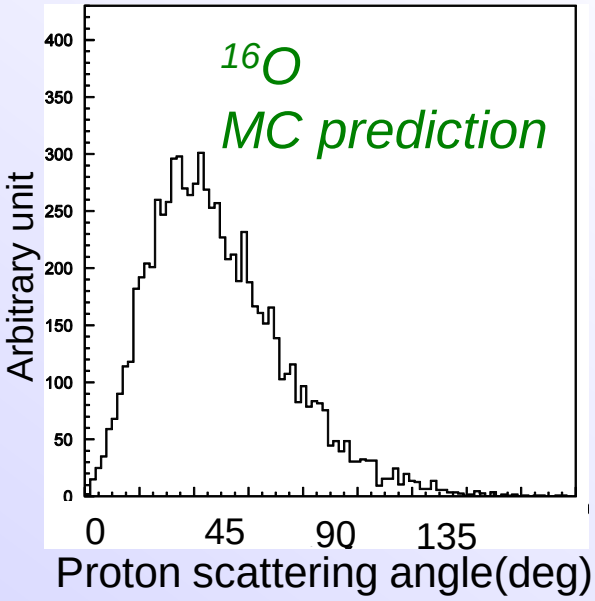
- ✓ cross section around a few GeV is suppressed
- ✓ small Q^2 region is suppressed

Nuclear effect(Nucleon re-scattering)

Nucleon re-scattering program
is based on the experimental data collected by H.W. Bertini
These data are same as GCALOR and MECC7



Below 225MeV/c ➔ Pauli blocking effect:
Nucleon almost escapes from nucleus
without interaction



Deflected angle of proton is 45 degrees
on average in 500<Pproton<1000MeV/c

Nuclear effect(Formation zone for πN interaction)

Distance from neutrino interaction point to
hadron production point (formation length) is considered

Formation length for hadron : $L=p/\mu^2$ μ = 0.08GeV^2 fitted by SKAT
(V.Ammosov@NuInt01)

➔ Reduces the interactions of generated hadrons
in high energy region

➔ but, effect is small in lower energy region

Summary

- NEUT has updates in QE, coherent π, DIS, and nuclear effect since NuInt01
- In QE and coherent π, improved model with better agreement with current data is available, comparisons with the data from forthcoming experiments are desirable
- Neutrino interaction simulation is required to achieve better accuracy in future neutrino oscillation experiments
- *Now NEUT is not only for SK,K2K,SB, and T2K*
  We hope NEUT is used in a lot of experiments

Backup

Quasi-elastic

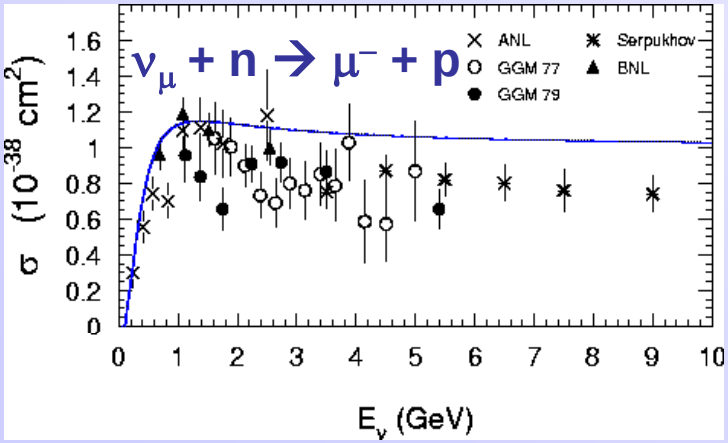
As for *free nucleon,*

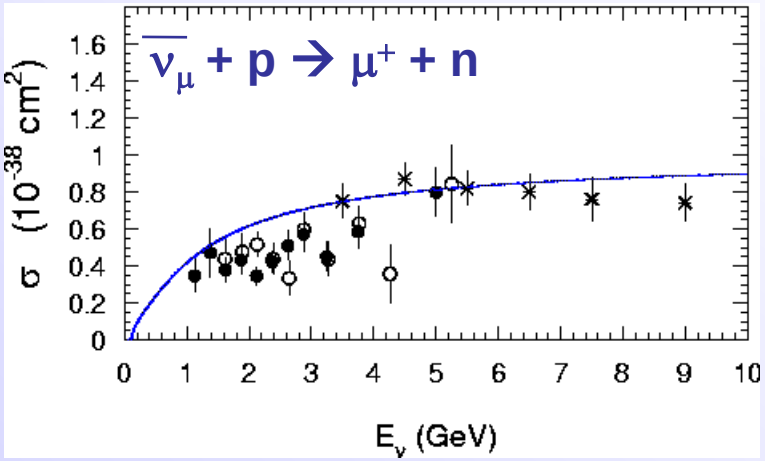
Based on C.H.L. Smith (Phys. Rep. 3,261(1972))

Dipole form factor is used ➔ problem of FF and M_A

As for *bound nucleon*,

Based on Smith-Moniz(Fermi gas)
(Nucl.Phys.B43 605(1972),erratum-ibid.B101 547(1975))





M_A is set to be 1.1GeV/c^2 for both QE and 1π
based on K2K analysis(PRL 90, 041801)

Deep inelastic scattering
(summary of Bodek-Yang correction for GRV94lo)

1. Bjorken scaling x→ x_w

$$x_w = x\frac{Q^2 + B}{Q^2 + Ax}$$

A : target mass effect
higher twist effect
B : nonzero F_2 as $Q^2 \to 0$

2. Structure function F_2

$$F_2(x) \to \frac{Q^2}{Q^2 + C} F_2(x_w)$$

In order to fit both intermediate-x and low-x

3. d/u ratio

$d_v \to d'_v(d_v,u_v)$
$u_v \to u'_v(d_v,u_v)$

Correction for conversion $F_2^d \to F_2^n$

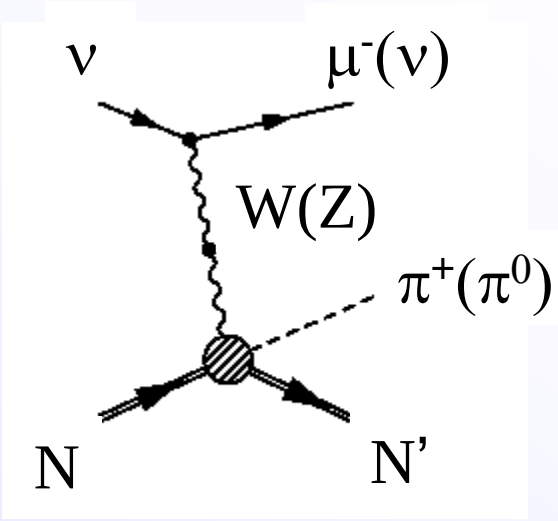
4. Longitudinal R

$$2xF_1 = F_2 \frac{1 + 4Mx^2/Q^2}{1 + R}$$

Correction for spin of target particle

Coherent π production

- K2K-SciBar group reports that CC coherent pion production is not observed at about 1GeV
- In CC, $\nu + {}^{16}O \rightarrow l^{-(+)} + {}^{16}O + \pi^{+(-)}$ produces a charged lepton, effect of lepton mass on cross section is not negligible at lower energy



$$\frac{d\sigma^{\pi+}}{dxdy}\ (\text{CC}) = 2\frac{d\sigma^{\pi 0}}{dxdy}\ (\text{NC}) \times \left\{ \left(1 - \frac{1}{2}\frac{Q^2_{\min}}{Q^2 + m^2_\pi} \right)^2 + \frac{1}{4} y \frac{Q^2_{\min}\left(Q^2 - Q^2_{\min}\right)}{\left(Q^2 + m^2_\pi\right)^2} \right\}$$

x,y : *Bjorken scaling* *where* $Q^2_{\min} \propto m_{lepton}, y \quad Q^2 \propto x, y$

(Rein & Sehgal Nucl. Phys. B233,29 Rein & Sehgal hep-ph/0606185)

Coherent π production

- Kartavtsev, Paschos & Gounaris model is tried (Phys. Rev. D **74**, 054007 (2006)) as one option
- Kartavtsev model describes kinematics and cross section taking into account lepton mass

Summary of Kartavtsev model

- Based on the partial conservation of axial current(PCAC), same as Rein & Sehgal
- Adler relation(formula for weak current cross section) is not used
- need π-nucleus scattering experimental data