Prospect of neutrino interaction and nuclear effect studies

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Introduction

T2K has collected ~ 11 x 10^{20} POT = 14% of T2K Goal

~ 7 x 10^{20} POT (neutrino-mode)

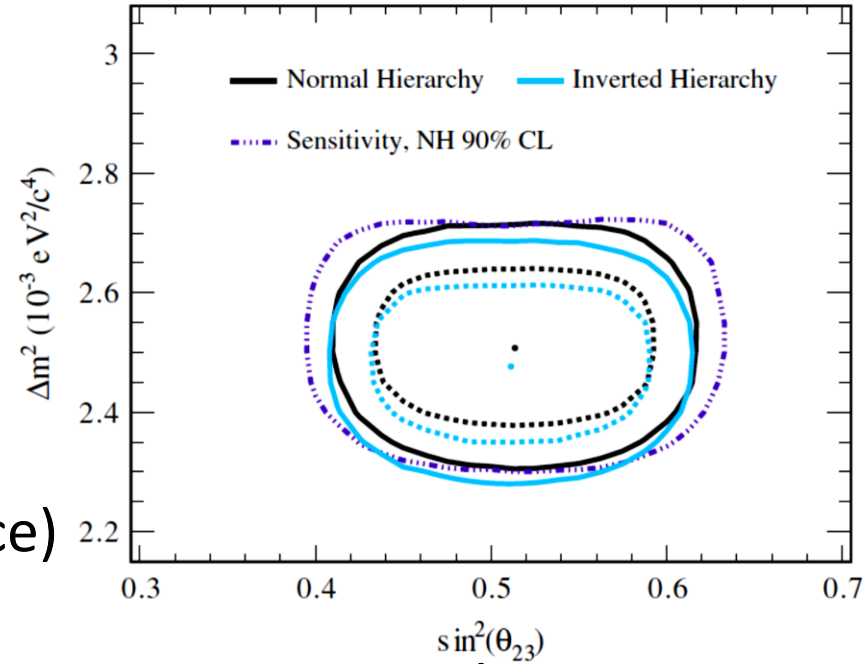
~ 4 x 10^{20} POT (anti-neutrino mode)

ν_μ disappearance analysis

$\sin^2\theta_{23}$ [0.427, 0.596]

Δm^2_{32} [2.34, 2.68]

($\times 10^{-3}$ eV^2/c^4)



# of candidates : ***120 events***

Systematic errors

(on # of events for ν_μ disappearance)

Total 7.7%

Flux and ND280/SK Common cross-sections

2.7%

Independent cross-sections (non-cancelling)

5.0%

Necessary to reduce neutrino interaction systematic uncertainty

Neutrino-nucleon interactions from 100 MeV ~ a few GeV

Charged current quasi-elastic scattering (CCQE)

$\nu + n \rightarrow l^- + p$

Neutral current elastic scattering

$\nu + N \rightarrow \nu + N$

Single meson productions

$\nu + N \rightarrow l + N' + \pi\ (\eta, K)$

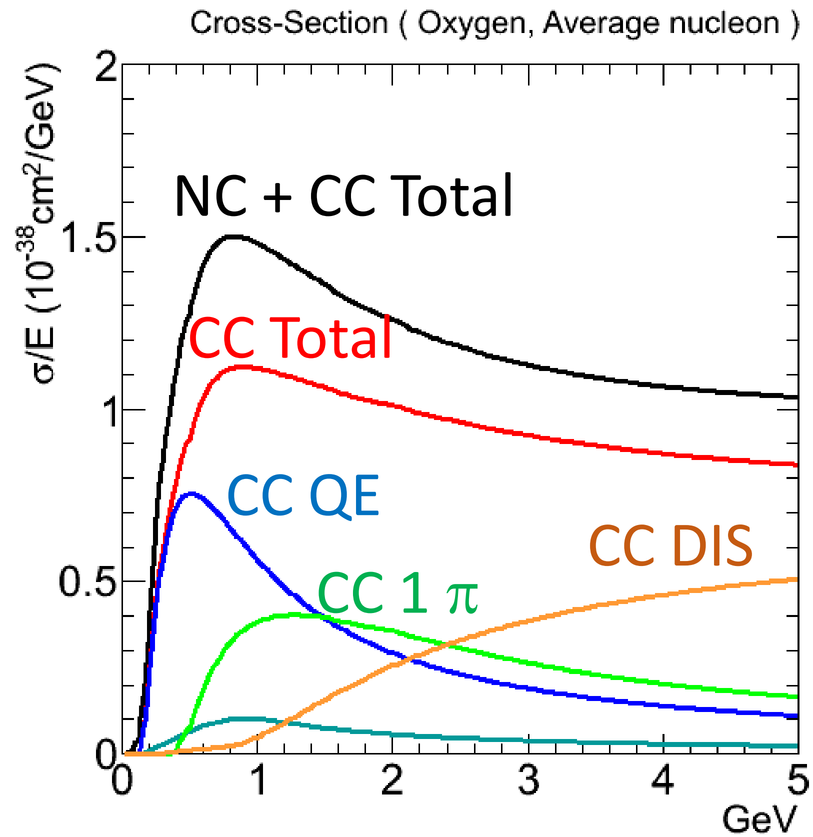
Single photon productions

(radiative decay of resonance)

$\nu + N \rightarrow l + N' + \gamma$

Deep (/ shallow) inelastic scattering

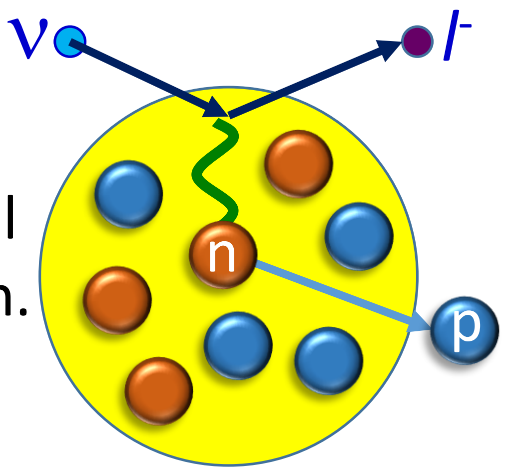
$\nu + N \rightarrow l + N' + m\pi(\eta, K)$



Charged current quasi-elastic scattering and single π production dominates in the T2K energy region.

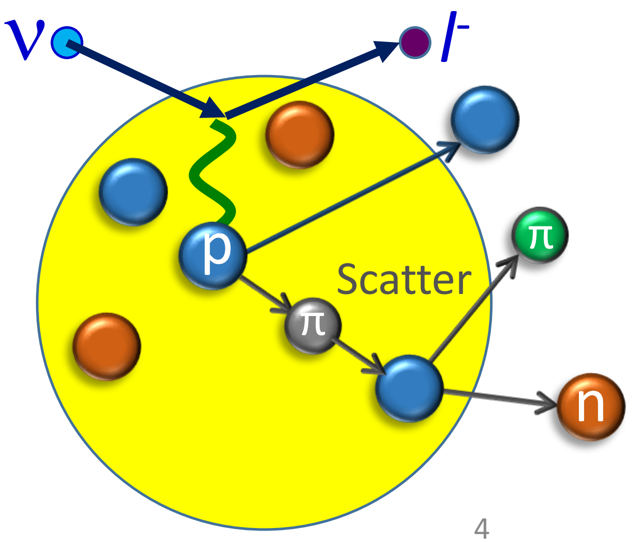
Neutrino-nucleus interactions from 100 MeV ~ a few GeV

Most of the neutrino interaction targets are in nucleus.
Different from the 'free' nucleon.



Target nucleon is in the nuclear medium (matter)
Impulse approximation and Fermi-gas model
works fairly well in this energy region.

Interacted nucleon or produced mesons interact
with the other nucleons in nucleus,
so-called final state interactions.

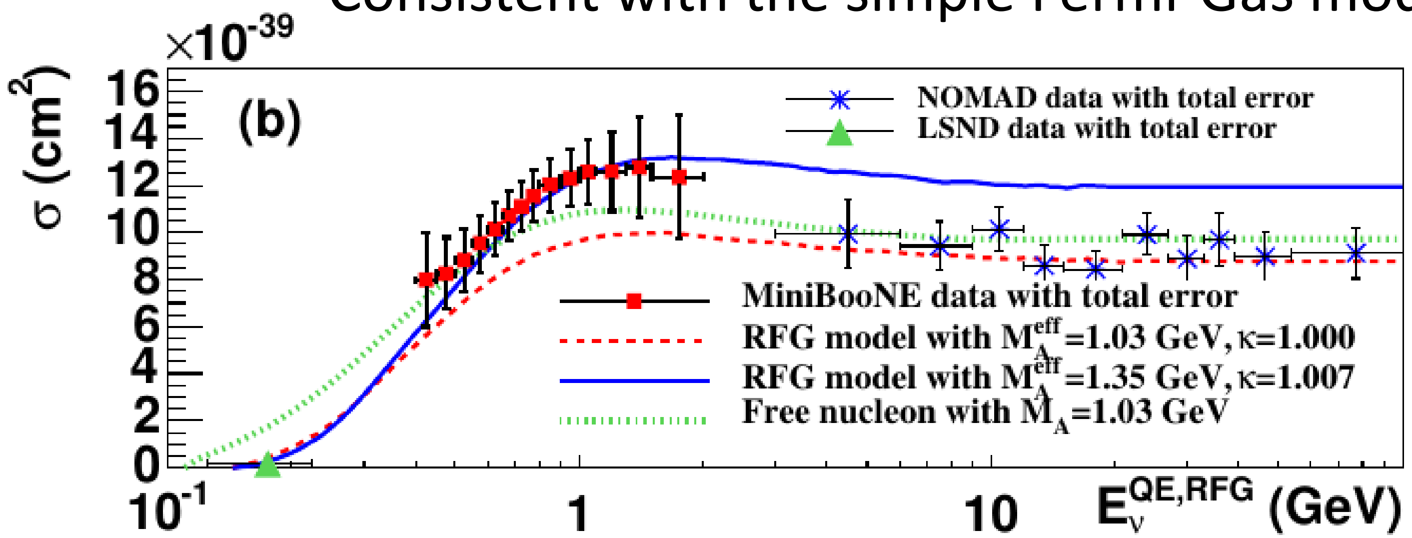


However, this simple models (treatments)
are not precise enough
for the recent experiments.

Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

Current (experimental) situation

- Low energy experiments (K2K-SciFi, MiniBooNE, E_ν < a few GeV)
  1) small q^2 or very forward region
     seems to have larger suppression than naive model.
  2) interaction probability (cross-section)
     seems to be larger than expected.
- Medium energy experiment (MINERνA, < E_ν > ~ 3.5 GeV),
  discrepancies seem to be smaller.
- High energy experiment (NOMAD, < E_ν > ~ 24 GeV)
  Consistent with the simple Fermi-Gas model...



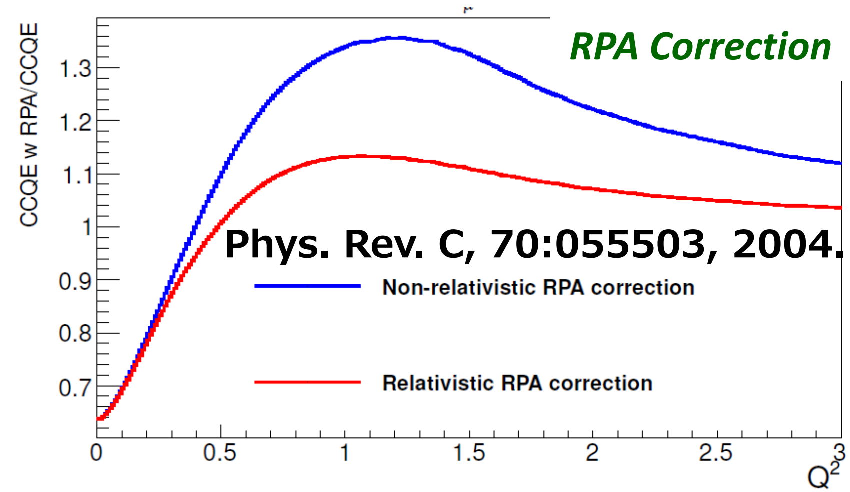
Phys. Rev. D81, 092005 (2010)

Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

Several possible improvements have been proposed.

- Random phase approximation (RPA) correction

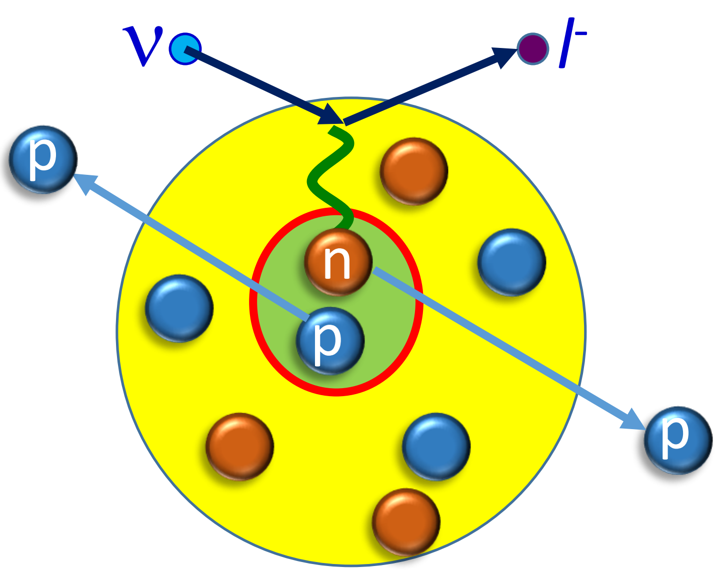
  the presence of strongly interacting nucleons in nucleus may change the he weak interaction strength

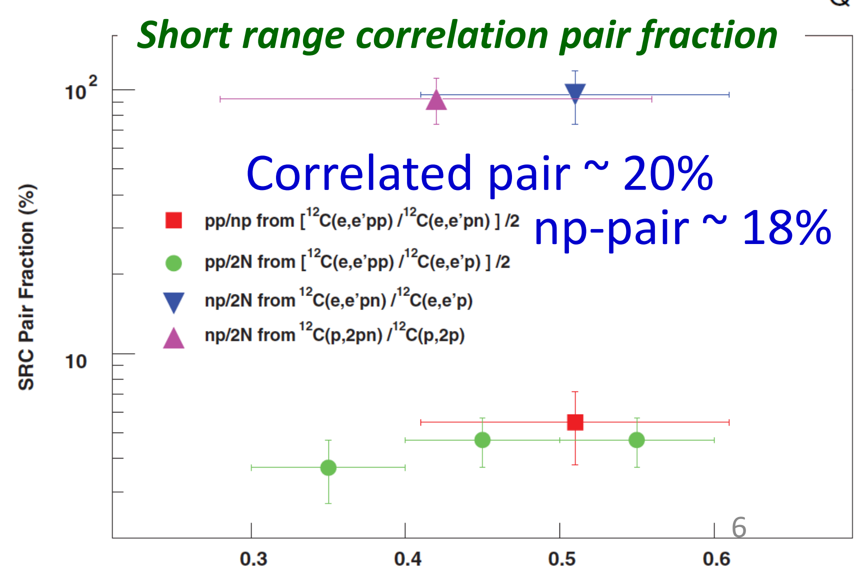


- Multi-nucleon effects

  Interactions with strongly coupled nucleons.

  Confirmed w/ electron scat. exp.



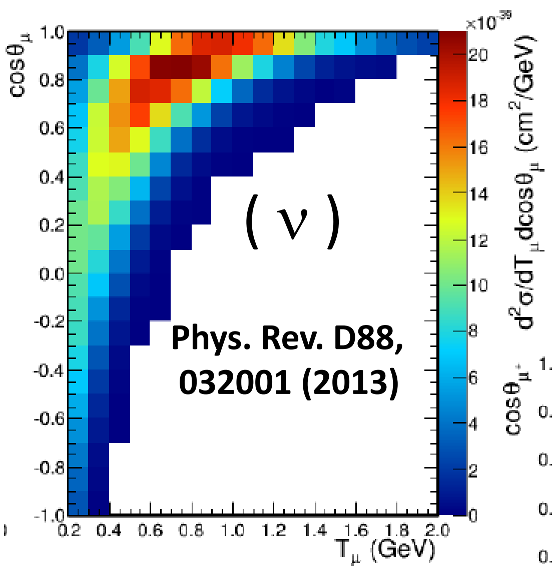


Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

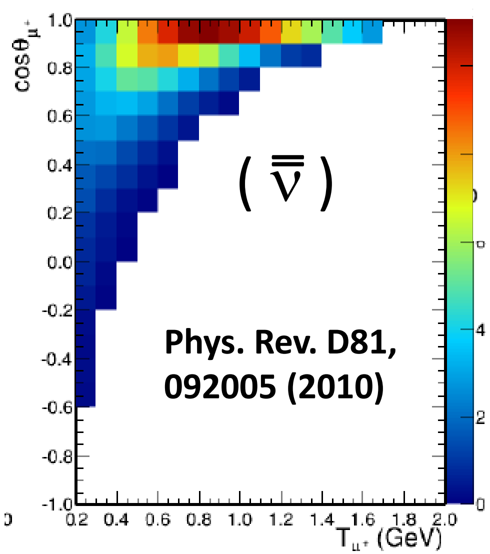
~ Fit existing data sets with new models ~

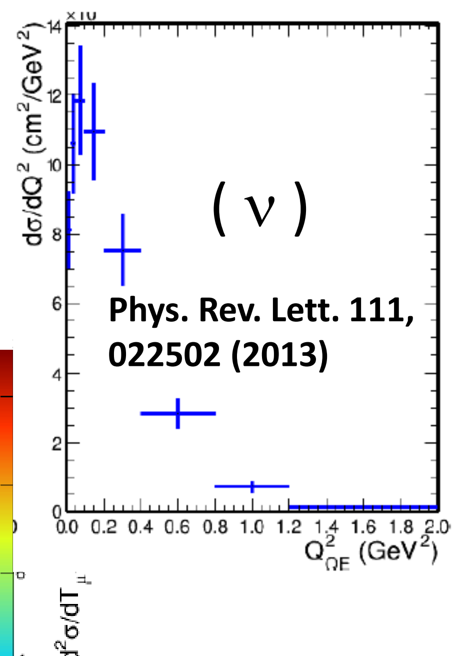
a) Relativistic Fermi Gas model with RPA correction (Nieves et al.)
+ Multi-Nucleon interactions (Nieves et al.)

b) Spectral function model (A. Ankowski, O. Benhar et al.)
+ Multi-Nucleon interactions (Nieves et al.)

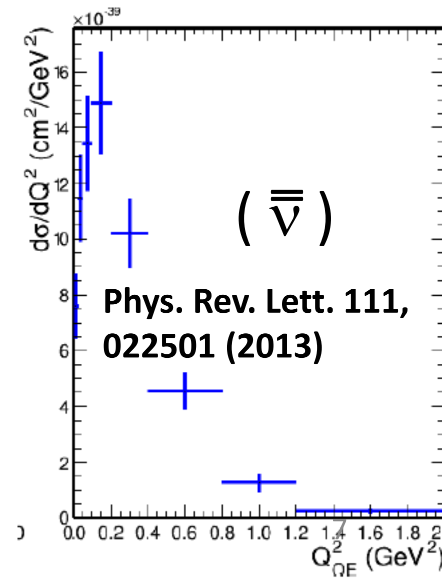


MiniBooNE
CCQE
2D ($\cos\theta_\mu$, T_μ)



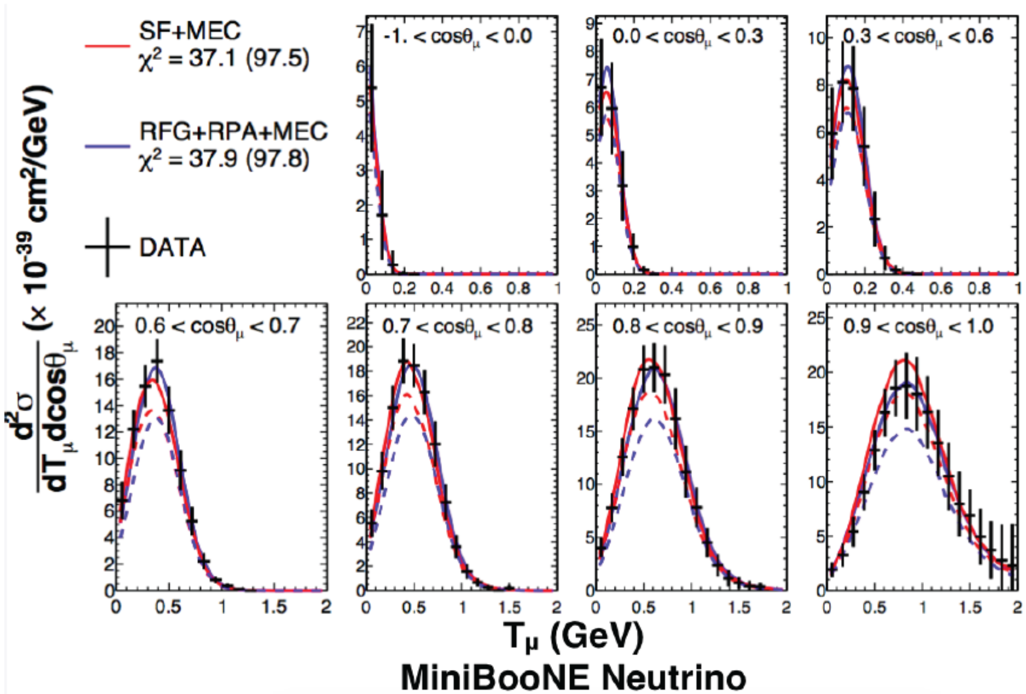


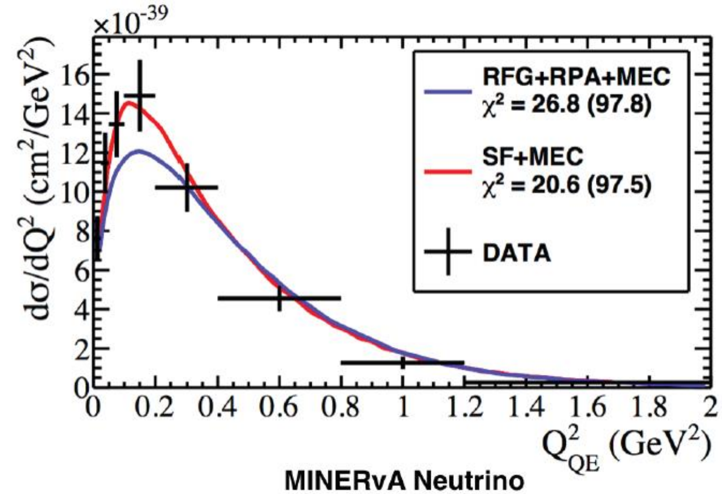
MINERnA
CCQE
1D (q^2)



Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

~ Fit existing data sets with new models ~





MEC : Meson exchange current
(Short range force mediated by meson)

Model	M_A (GeV/c^2)	P_F (MeV/c)	MEC fraction	χ^2 / # of D.O.F.
RFG with RPA + MEC	1.15 ±0.03	223 ±5	27% ± 12%	97.84/195
Spectral Function + MEC	1.33 ±0.02	234 ±5	0 (at limit)	97.46/196

* Additional normalization factors are included for MiniBooNE data

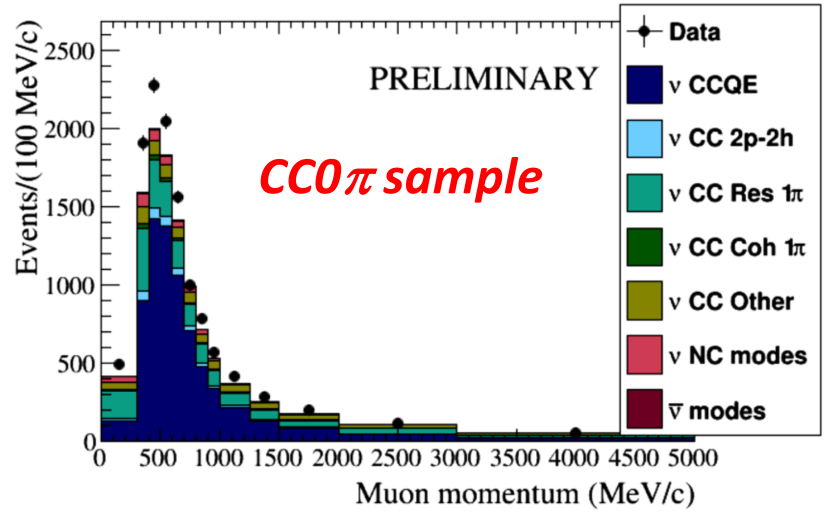
Selection of the model based on the fit is difficult at this moment.
Also, some tensions between data sets were observed.

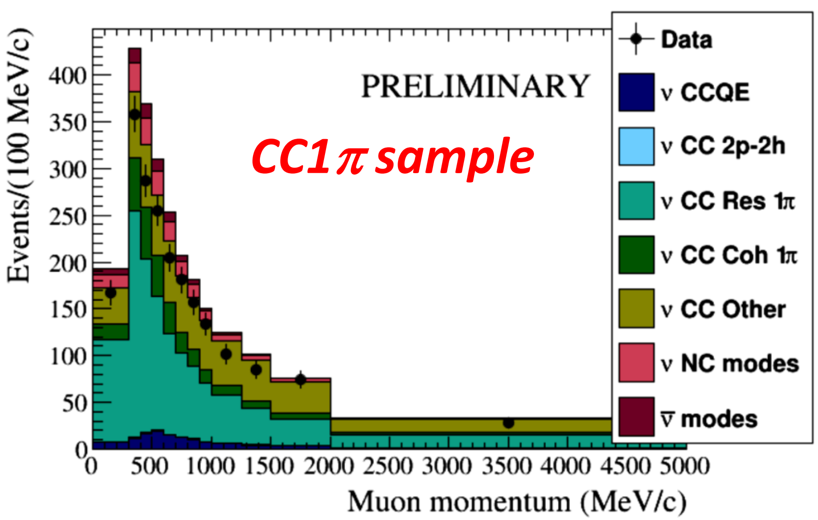
Neutrino-nucleus interaction studies in T2K

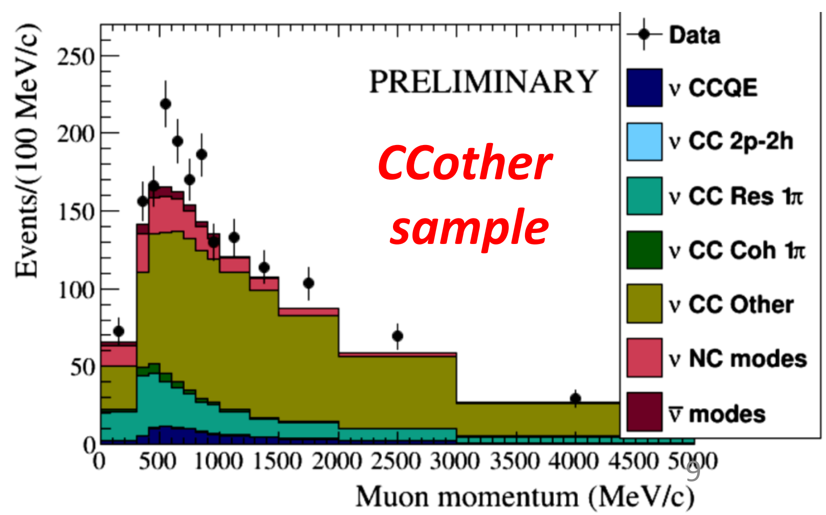
For the oscillation analyses, we performed the fit with ND280 data to determine/ constraint the neutrino interaction parameters and neutrino flux simultaneously.

3 sub-samples from neutrino running

- Events with μ^- and no pion ($CC0\pi$)
  CCQE enriched
- Events with μ^- and 1 $\pi^{\pm}$ ($CC1\pi$)
  CC 1π enriched
- Other events with μ- (CC Other)
  CCDIS enriched





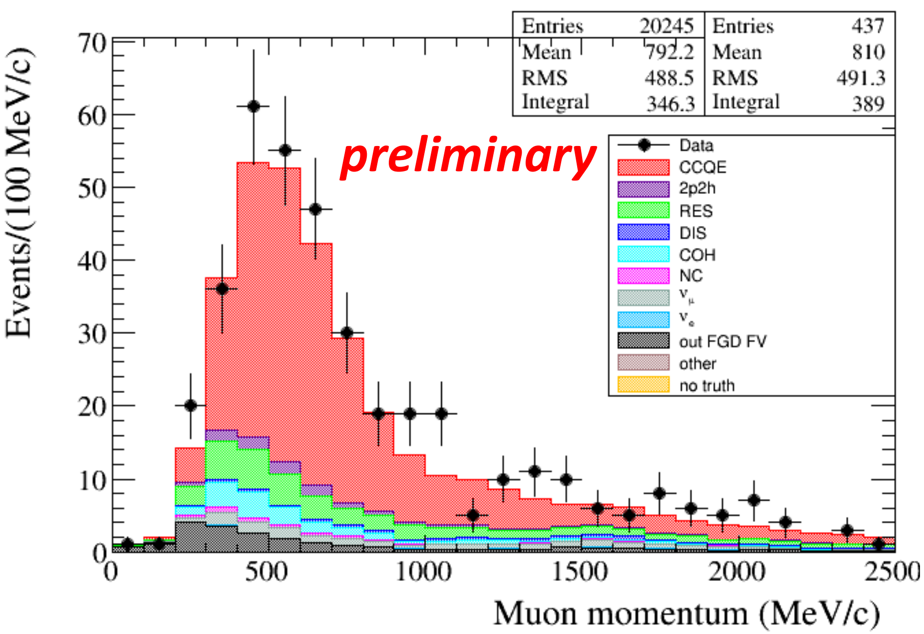


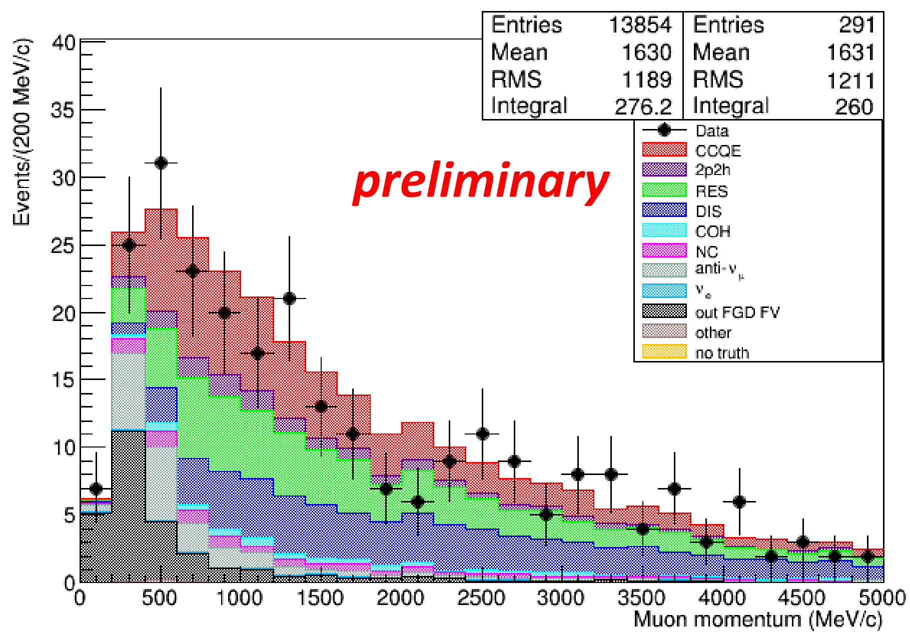
Neutrino-nucleus interaction studies in T2K

For the oscillation analyses, we performed the fit with ND280 data to determine/ constraint the neutrino interaction parameters and neutrino flux simultaneously.

2 sub-samples of $\bar{\nu}$ in anti-neutrino running period.

- Events with μ^+ and only 1 track reconstructed
  CCQE enriched
- Events with μ^+ and there are more than 1 track reconstructed
  Inclusive (less CCQE)





(ν candidaes in $\bar{\nu}$ running is also used)

Neutrino-nucleus interaction studies in T2K

Neutrino interaction and flux parameter fit using the ND280 data sets

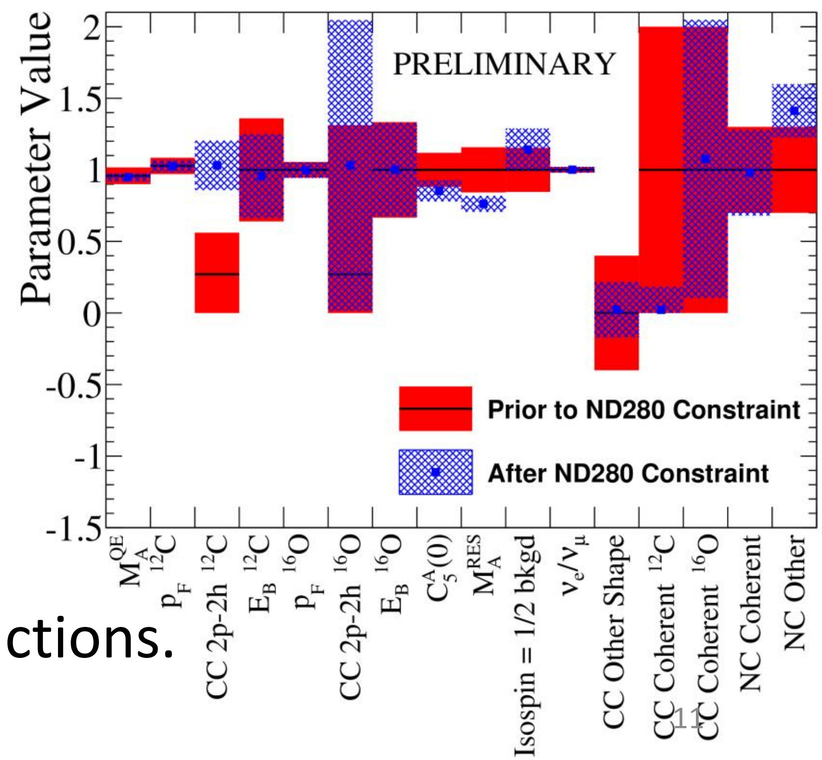
Parameter *preliminary*	Prior	Fit result
CCQE M_A (GeV/c^2)	1.15 ± 0.07	1.13 ± 0.03
PF (Carbon) (MeV/c)	223.0 ± 12.3	222.7 ± 8.83
MEC fraction (%)	27.0 ± 29.0	103.1 ± 17.2

In the fit, not only these parameters but other parameters including flux were fit simultaneously.

Therefore, these values can not be compared directly with the results from external data fits.

T2K ND280 data sets seem to require MEC-like interactions.

Need further dedicated studies!



Neutrino-nucleus interaction studies in T2K

Cross-section measurements with the near detectors

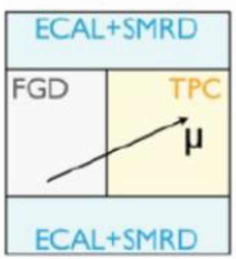
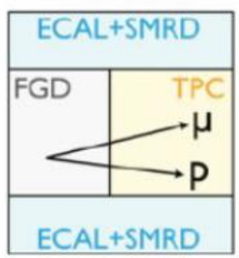
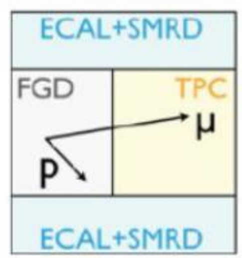
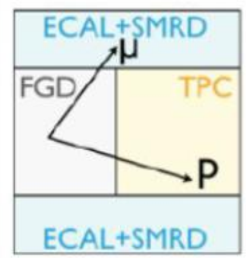
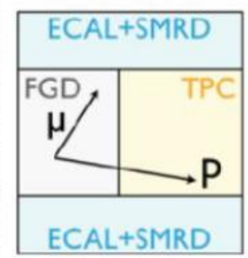
- We have studied CCQE using off-axis detector. **(arXiv: 1411.6264)**

  Obtained (effective) $M_A = 1.26^{+0.21}_{-0.18}$ GeV/c^2 (absolute).

  (without recent multi-nucleon interaction models.)
- Further detailed study of

  CCQE and Multi-nucleon interactions are required.
- Now we are trying to use proton track information

  and compare with recent models with additional interactions.

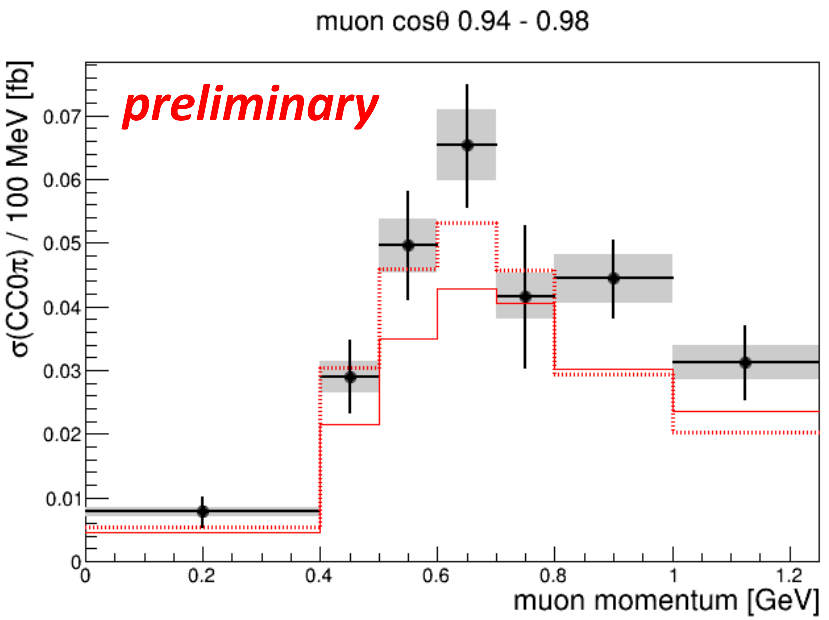
	(1)	(2)	(3)	(4a)	(4b)
CCQE topology					
topology description	• μ_{cand} is FGD-TPC track • p_{cand} not reconstructed	• both μ_{cand} and p_{cand} are FGD-TPC tracks	• μ_{cand} is FGD-TPC track • p_{cand} is FGD-only track	• p_{cand} is FGD-TPC track • μ_{cand} is FGD track: a) not fully contained b) FGD-only track	

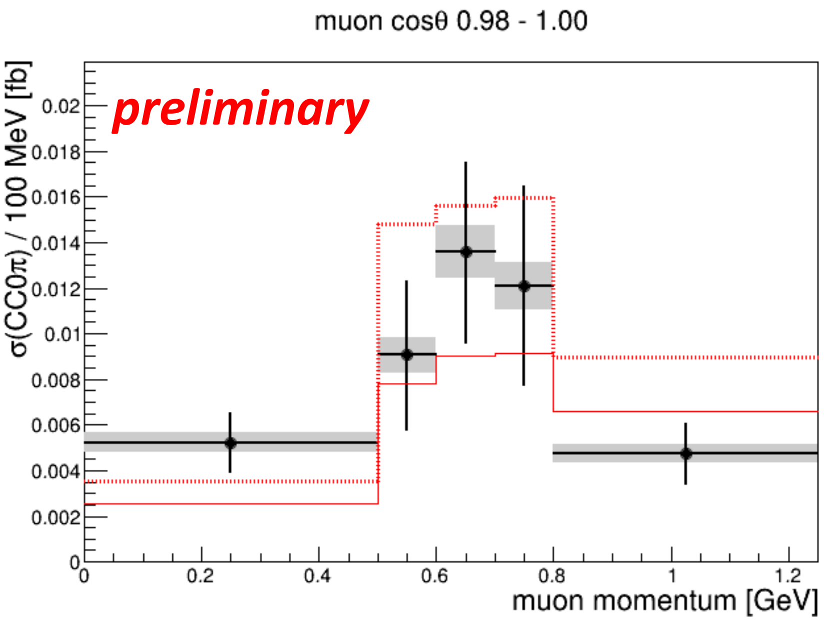
Neutrino-nucleus interaction studies in T2K
Cross-section measurements with the near detectors

Data sets are compared with two model predictions:

Martini et al. RPA + Multi-nucleon interactions
Phys. Rev. C 80 065501 (2009)

Nieves et al. RPA + Multi-nucleon interactions
Phys. Rev. C 83 045501 (2011)





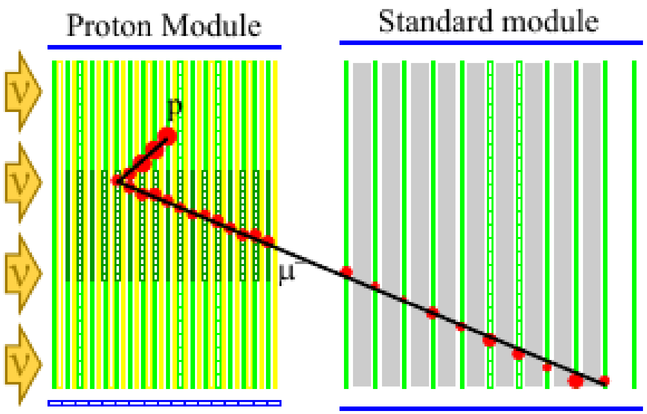
Further studies are on-going to test the models and also, to estimate the contributions from multi-nucleon intearctions.

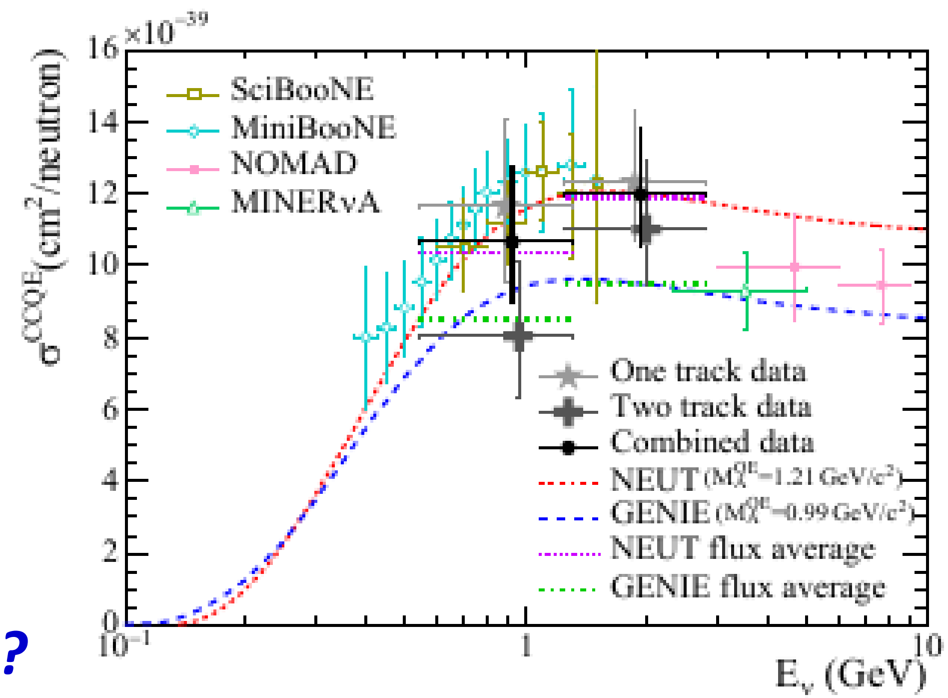
Neutrino-nucleus interaction studies in T2K

Cross-section measurements with the near detectors

We also studied CCQE using proton track with T2K-INGRID detector.

(on-axis ~ higher energy region)





Single track (μ^- only) and
Two track (μ^- + p) samples
gave slightly different results.

Incompleteness of the model?

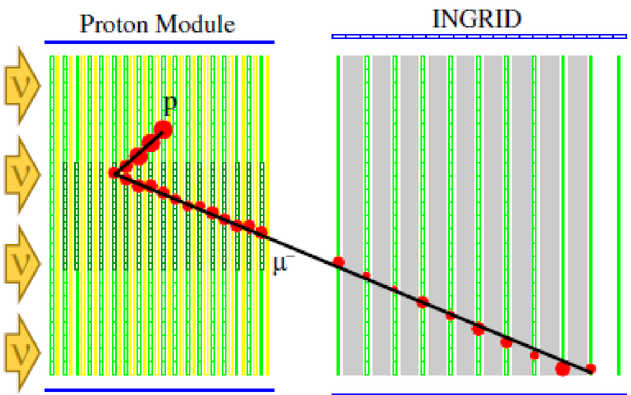
Interesting to study the energy dependence
using both on-axis and off-axis detector data sets.

Activities (~ energy deposit) around the vertex is
also expected to provide additional information.

Neutrino-nucleus interaction studies in T2K

Cross-section measurements with the near detectors

On-Axis detector (INGRID) has scintillator module
and Iron-scintillator composite modules.

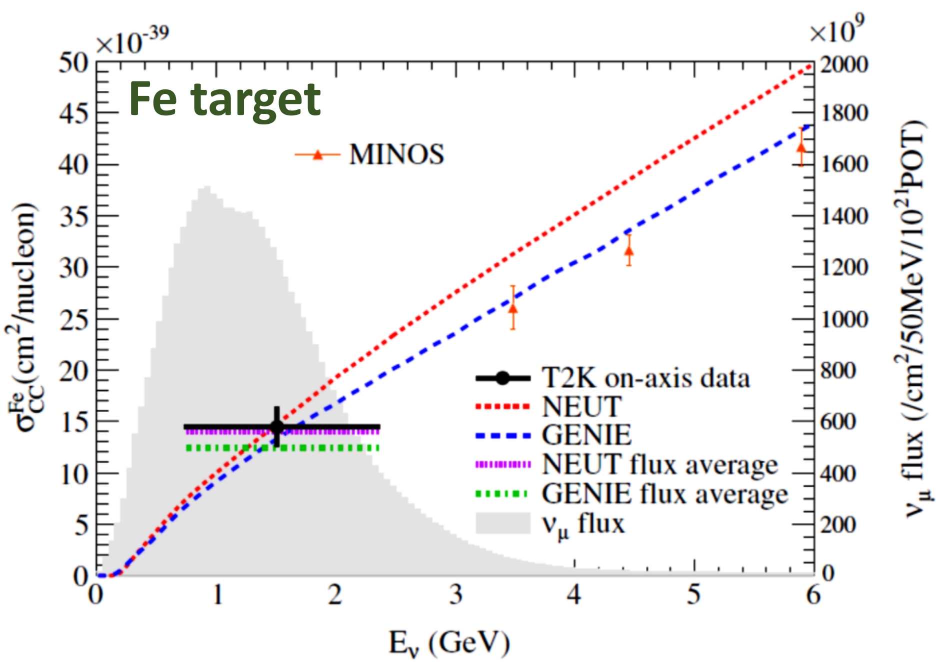


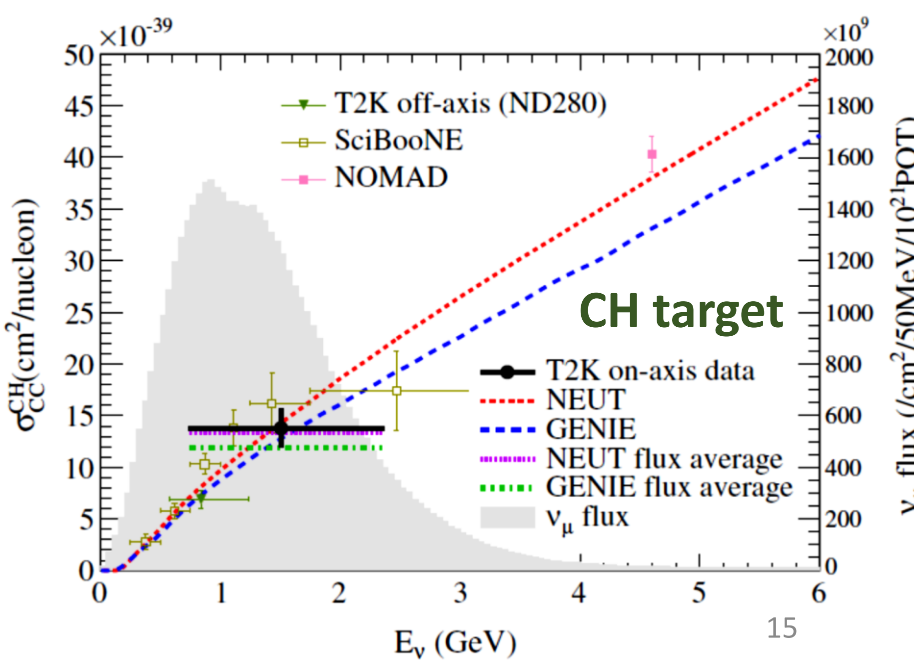
Inclusive cross-section measurement

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = \mathbf{1.047} \pm 0.007\ (\,stat.\,) + 0.035\ (\,syst.\,)$$

Phys. Rev. D 90, 052010 (2014)

Fe/C inclusive cross-section ~ 5% difference





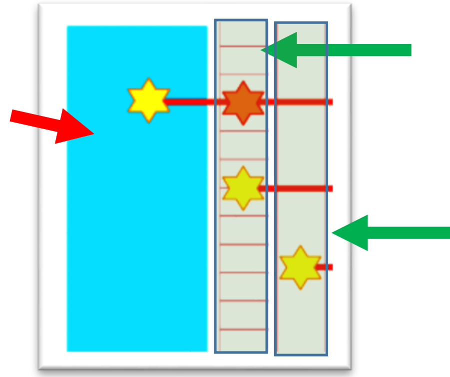
Neutrino-nucleus interaction studies in T2K

Cross-section measurements with the near detectors

Study of nuclear dependence ~ Use passive water layers in ND280

(One example of the on-going study ~ CC π^+ production)

Passive Water Layer

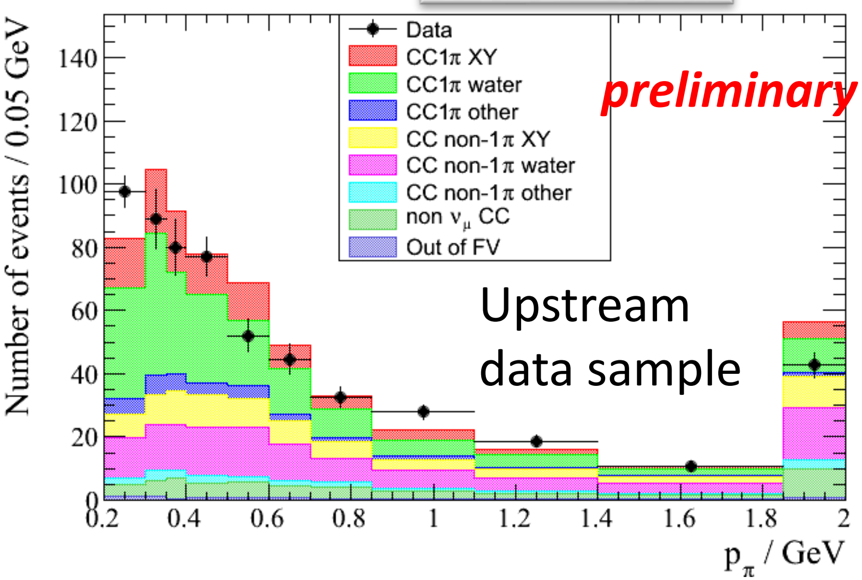


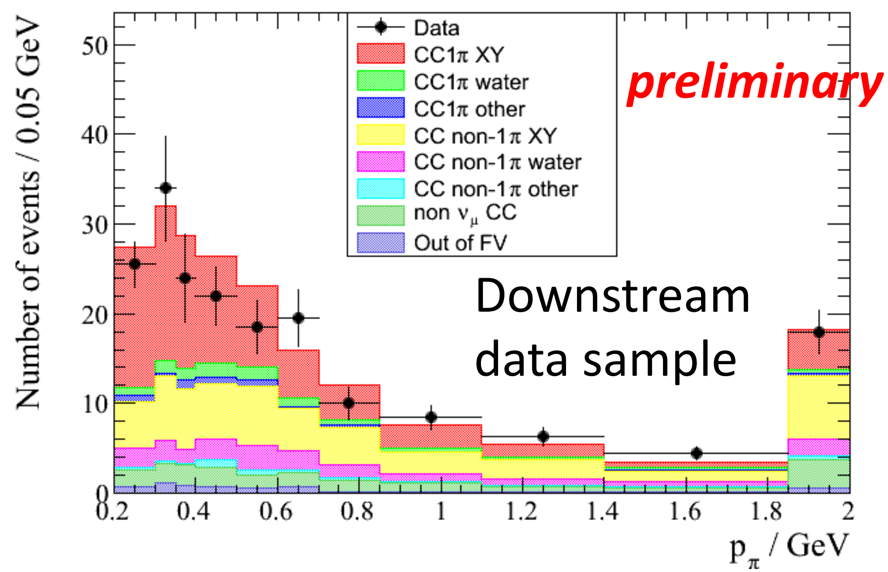
Upstream scintillator layer

Contain H_2O + CH interactions

Downstream scintillator layer

CH interactions



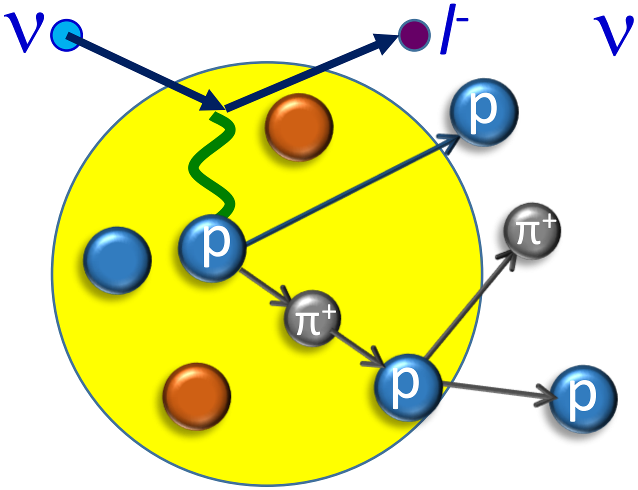


We also working on the CCQE (-like) interactions.

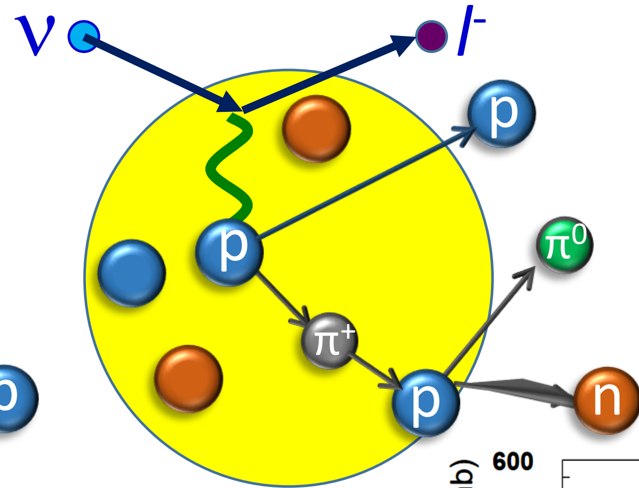
Nuclear effects ~ pion interaction in nucleus

Pion interactions in nucleus is also important
because these interactions affect determination of interaction mode.

Inelastic scattering

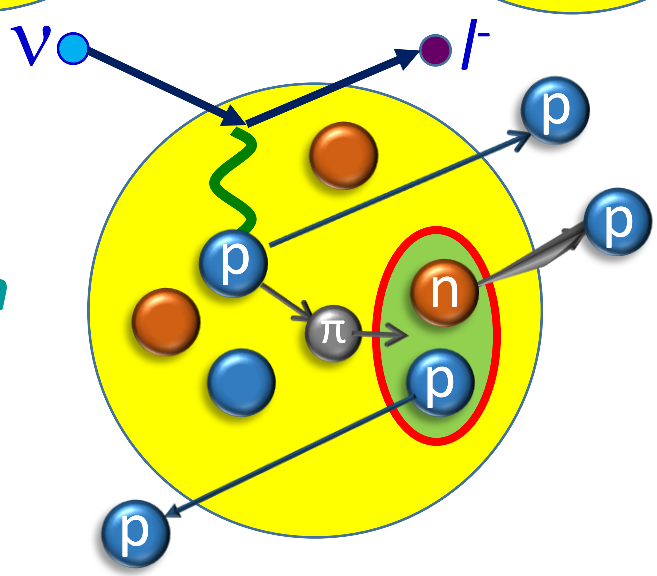


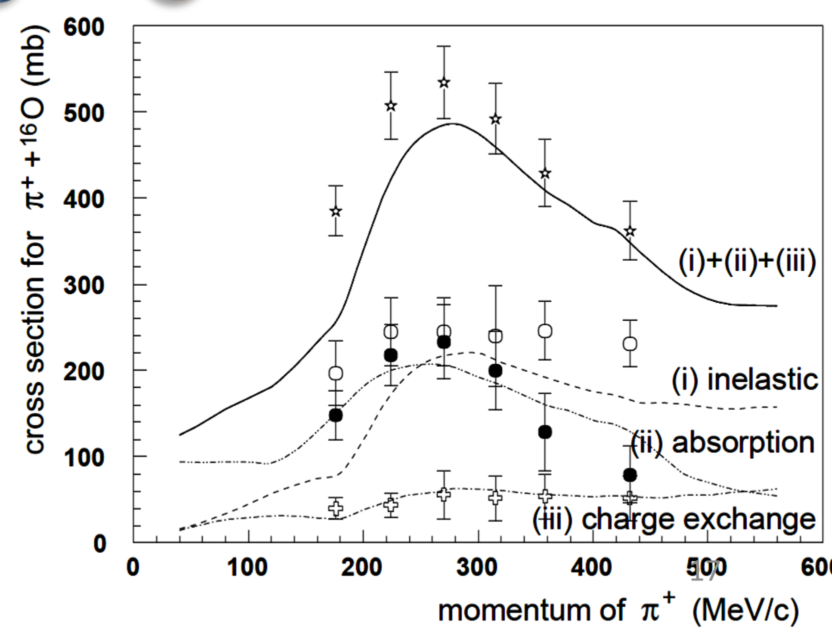
Charge Exchange



However, existing data have ***~ 30 %*** errors.
Not so much data above Δ region.

absorption



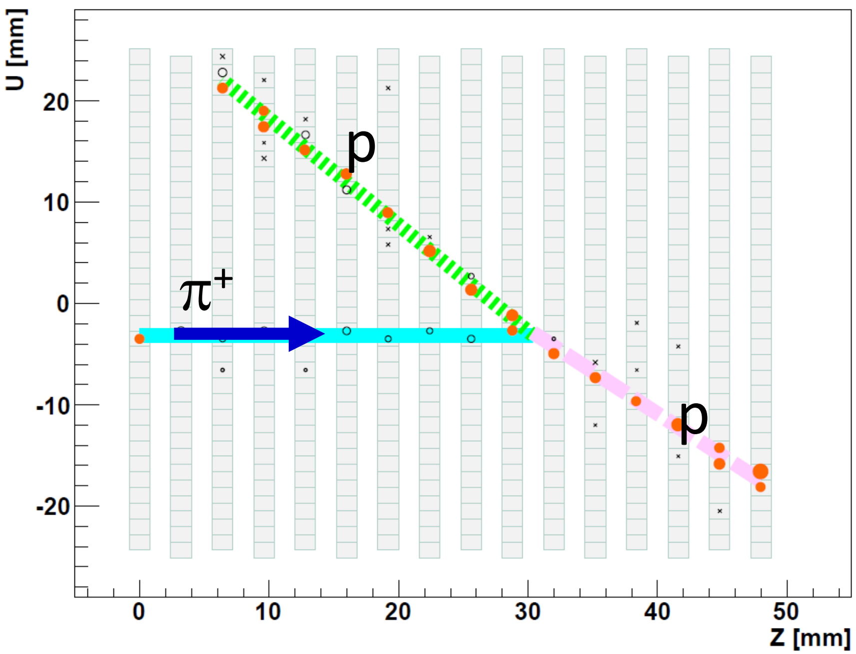


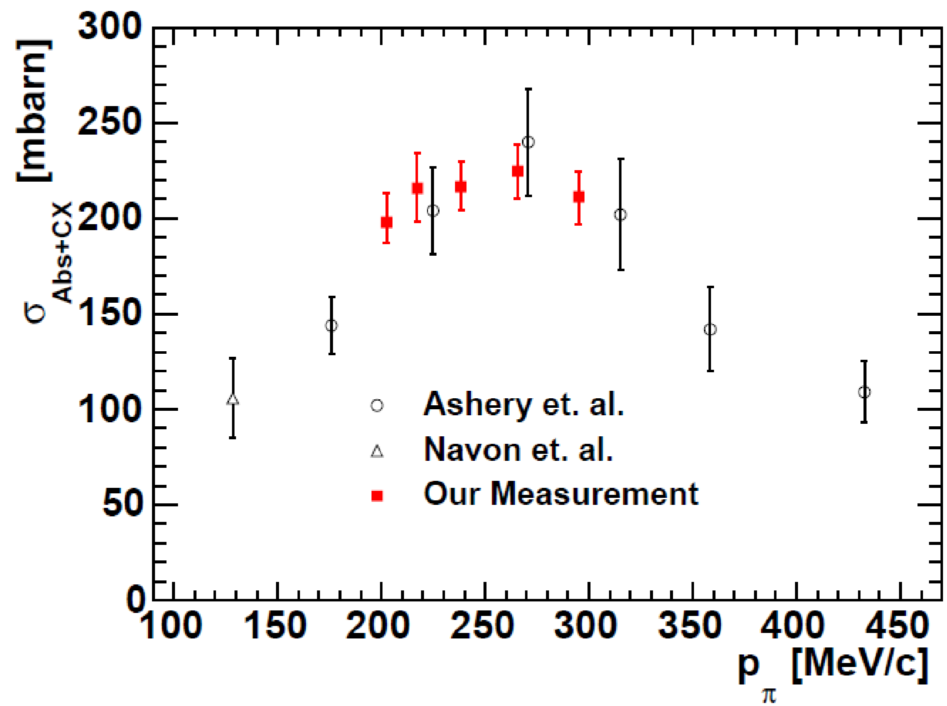
Nuclear effects ~ pion interaction in nucleus

Recently DUET experiments measured
absorption + charge-exchange cross-sections.

Absorption candidate events

arXiv:1506.07783 (Phys. Rev. C Accepted)





Almost back to back protons are observed after absorption.
(Correlated pair nucleon absorbed π^+ ?)

Error has shrunk less than 10%
Simulation parameter tuning has been started.

Study to separate charge exchange from absorption is on-going.

Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

(personal thoughts)

1) ***CCQE and Multi-nucleon CCQE-like interactions***

1. Measured interaction rates:

   MiniBooNE found larger interaction rate
   of CCQE(+like) interactions.

   Atmospheric sub-GeV ν_e event rate
   seems to be consistent with M_A=1.2GeV/c^2.
   (simple relativistic Fermi-Gas model)

   But there are uncertainties of ν fluxes.

2. Suppressions in the small q^2 region / forward going leptons
   have been observed in various experiments:

   K2K, MiniBooNE, MINOS (preliminary), T2K.

Larger M_A (with simple Fermi-Gas model)
seems to reproduce these to some extent.

Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

(personal thoughts)

1) ***CCQE and Multi-nucleon CCQE-like interactions.***

Even though, low energy data (somewhat) agrees
with expectations with simple Fermi-Gas + larger M_A ,
it is far from satisfactory.

Because possible contributions are neglected in the model:

RPA, multi-Nucleon interactions,
Local density effects (local Fermi-Gas) or
Spectral function (momentum-potential distributions)
etc…

***And assumed true E_ν and reconstructed E_ν relation
are incorrect for Multi-nucleon interactions.***

However, current data sets are not sufficient
to justify or reject the models.

Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

(personal thoughts)

1) ***CCQE and Multi-nucleon CCQE-like interactions.***

   1) Further improvements of reconstruction tools and analyses (in T2K ND280) are essential.

      Example)

      Extensive use of the proton tracks and the energy deposit around the vertex will provide useful information.

      (Some indications in MINERνA results.)

   2) More neutrino and anti-neutrino data (of the T2K ND280)

      Still statistically limited to perform detailed analyses.

      Neutrino and anti-neutrino interactions have different $dq^2/d\sigma$.

      This may provide additional information on nuclear effects and dependences.

Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

(personal thoughts)

1) ***CCQE and Multi-nucleon CCQE-like interactions.***

With the current T2K ND280,
energy/momentum threshold (from track ID)
or energy resolution (from vertex activity) of protons
may not be sufficient to give definite answer.

Also, we need to understand the nuclear dependence,
i.e. difference between Carbon and Oxygen.

(Current ND280 can provide some info. but may not be sufficient.)

Therefore, we need additional information.
Experiments like MINERνA and MicroBooNE
will provide useful information.

However, the current issues seem to have energy dependence.
Also, Ar may be too large nucleus, unfortunately.

We need a sets of new detectors!

Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

(personal thoughts)

1) ***CCQE and Multi-nucleon CCQE-like interactions.***

Several new detectors have been proposed. Among of them,

a) Water + Scintillator 3D grid tracking detector (WAGASCI)

b) Introducing water based scintillator cells in FGD

c) Emulsion detector with water target

d) High pressure gas TPC with Neon

seem to be quite interesting and promising.

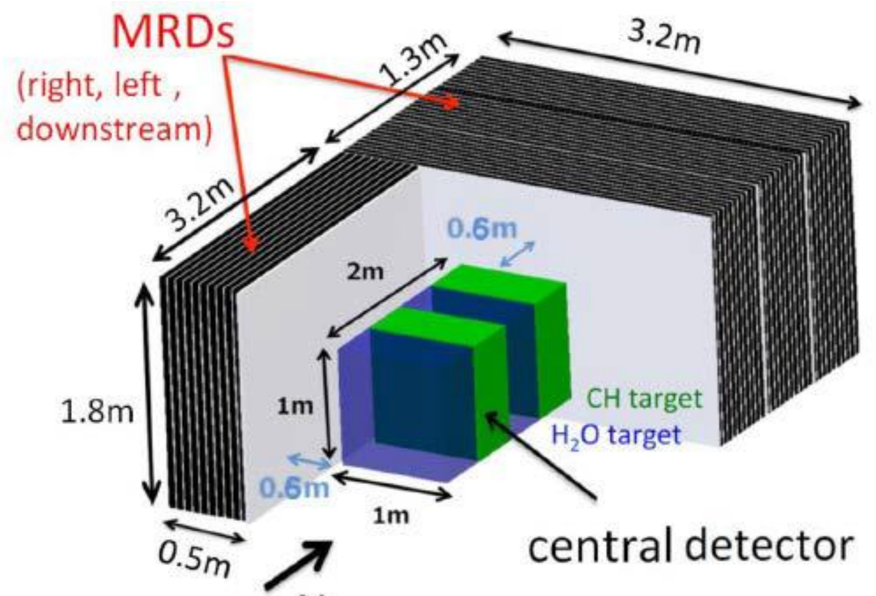
a) and b) are quite straight forward and will improve understanding of C/O differences.

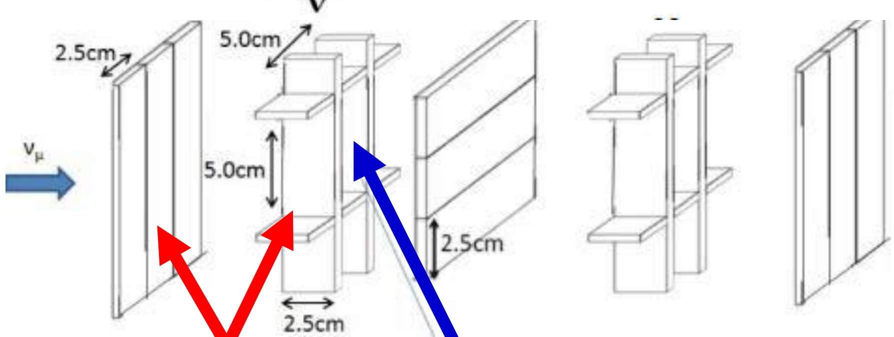
c) and d) are really attractive because they have low momentum threshold with fine tracking capabilities.

d) may need (quite a lot) of R&D, though.

~ New detectors ~

WAGASCI(T59)



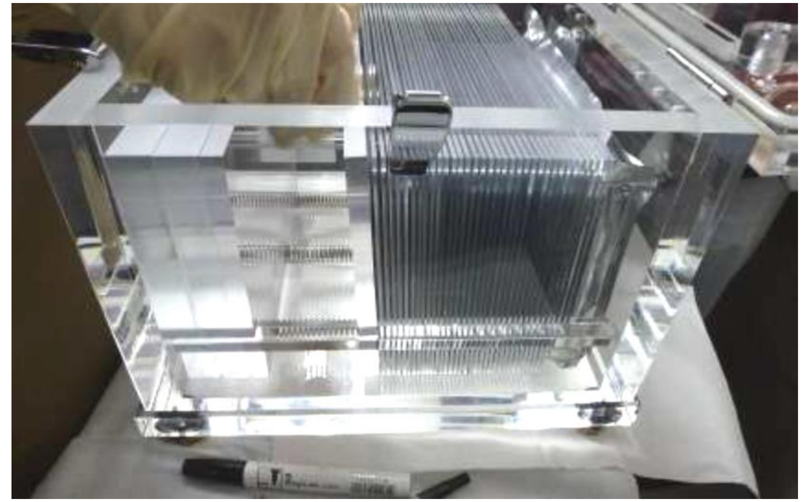


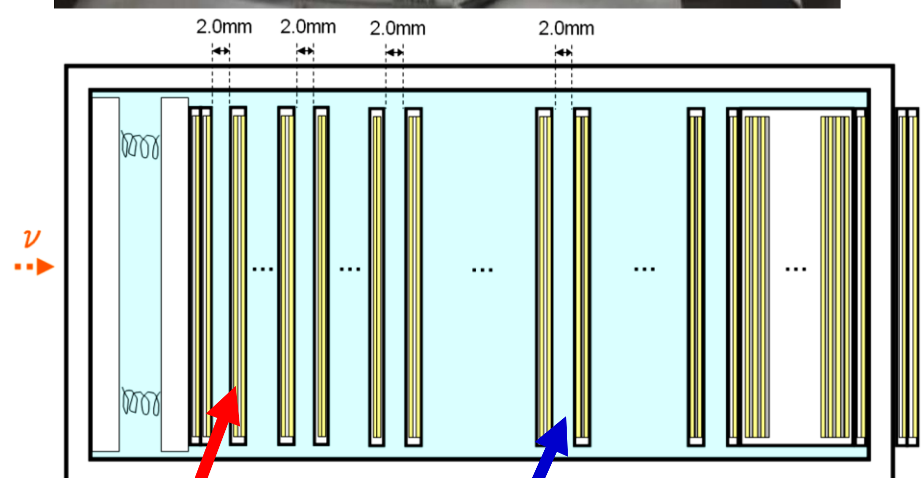
Plastic scintillator

Cells are filled with **H_2O** or **CH**

(Cell size is 5 x 5 x 2.5 cm³)

Emulsion detector(T60)





Emulsion films

in Water target chamber

(water layer : 2mm)

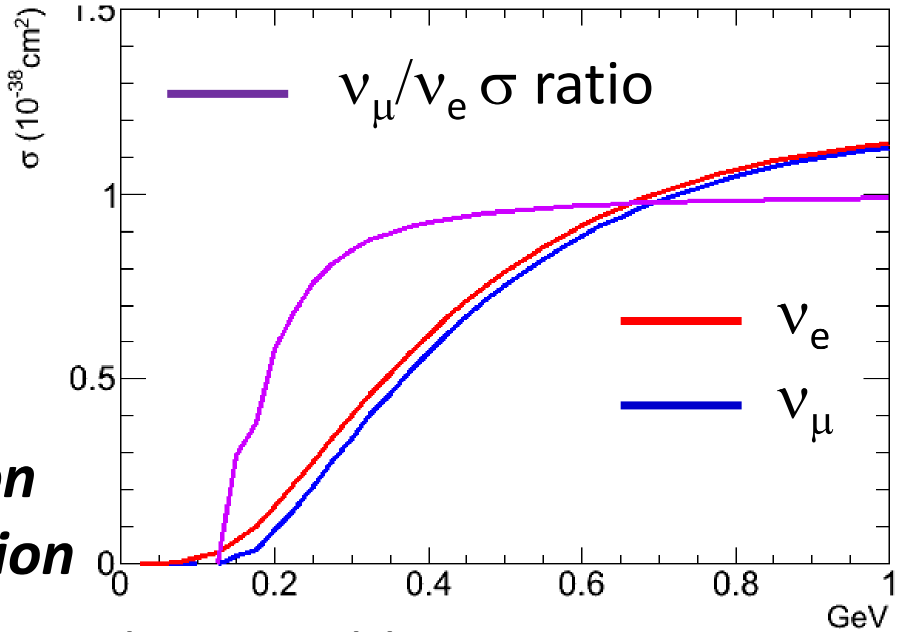
Neutrino-nucleus interaction studies to maximize neutrino oscillation sensitivity

(personal thoughts)

2) ***ν_μ / ν_e ratio***

Low energy σ (< 0.5 GeV) has nuclear model dependence.
It may not have large impact but need to be studied.

CCQE Cross-section (nucleon in Oxygen)



3) ***Single π production cross-section and π momentum distribution***

Rein-Sehgal (FKR) model is known to have problem in reproducing electro-pion production data.
Modified (improved) structure function is used in Neut but it is time to try more sophisticated models for comparison.
(At this moment, there seems no significant difference, though.)

Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

(personal thoughts)

4) ***π interactions in/with Carbon and Oxygen***

DUET experiment is expected to provide
cross-sections of π + C scattering.

However, p_{π} < 300 MeV/c.

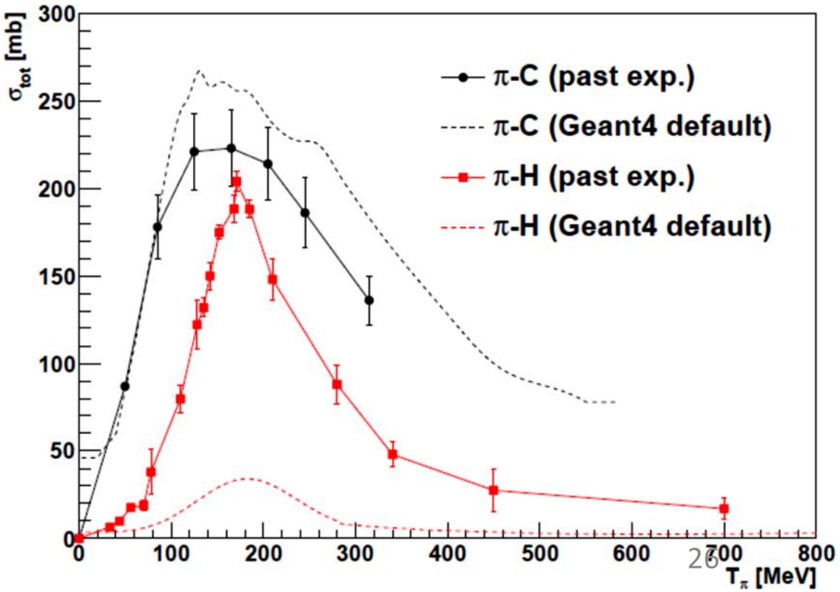
We need to have higher P_{π} data for the improvements of

a) π secondary interactions (FSI) in nucleus

and b) π interactions in the detectors.

GEANT4 is used to simulate
detector responses.

Precisions of π interactions
in the detector are important
to study neutrino intearctions.



Neutrino-nucleus interaction studies
to maximize neutrino oscillation sensitivity

(personal thoughts)

5) ***nucleon interactions in/with Carbon and Oxygen***

We need to find the way to improve nucleon interactions in the nucleus or in the detector.

6) ***Improvements of the neutrino interaction simulation programs***

Recently, collaborations with theorists are really working well to improve our understanding of the models and the simulation software.

We have to continue and expand these activities not only for the neutrino oscillation studies but also for the better understanding of the neutrino-nucleus interactions.

Summary

Uncertainties of

- neutrino-nucleus interactions,
- hadron interactions in nucleus and
- hadron interactions in detectors

are expected to be the largest sources
of the systematic errors in the oscillation analyses.

We have to improve analysis tools of ND280
for further detailed analyses of various interactions.

Already running or starting experiments in the world
are also expected to provide useful information.

However, we also need `optimized’ detectors
with sufficient statistics
for better understandings of these interactions
in the T2K energy region.

Summary

Recently, we are collaborating with theorists
to understand the interactions and it is really helpful.
We have to expand this kind of activities
to develop more accurate and reliable
neutrino-nucleus and detector simulation programs
and to assign appropriate systematic uncertainties.

All the studies of these interactions will help
in improving the atmospheric neutrino oscillation analyses
and proton decay search sensitivities.

fin.

backups and memos

Study of neutrino interactions

Past experiments

Bubble chamber ~ D_2 target

(quasi-) free neutron data as reference

Recent experiments

MiniBooNE

Mineral Oil Cherenkov detector

4π coverage

MINERnA

Fine grained tracking detector

Scintillator + other target material

Limited acceptance (< ~ 20 degree for μ etc.)

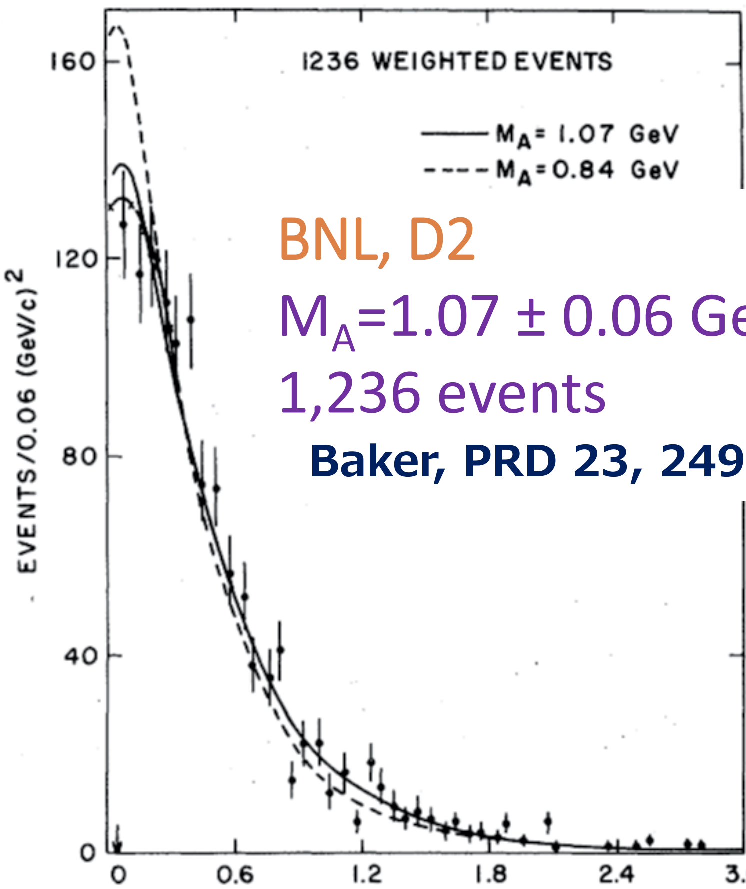
but sensitive to the heavy particles.

Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

Vector & Axial form factors

Vector part : Determined using electron scattering data

Axial part : Determined using neutrino scattering data (dipole form, parameter is M_A)



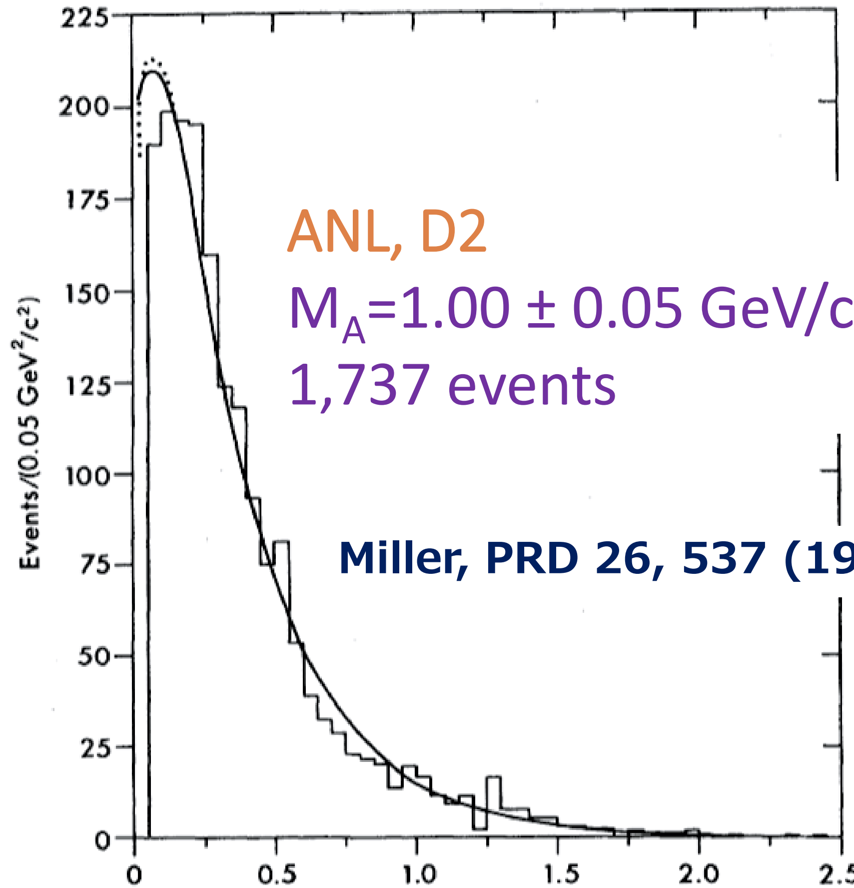
BNL, D2

M_A=1.07 ± 0.06 GeV/c^2

1,236 events

Baker, PRD 23, 2499 (1981)

$Q^2[(GeV/c)^2]$



ANL, D2

M_A=1.00 ± 0.05 GeV/c^2

1,737 events

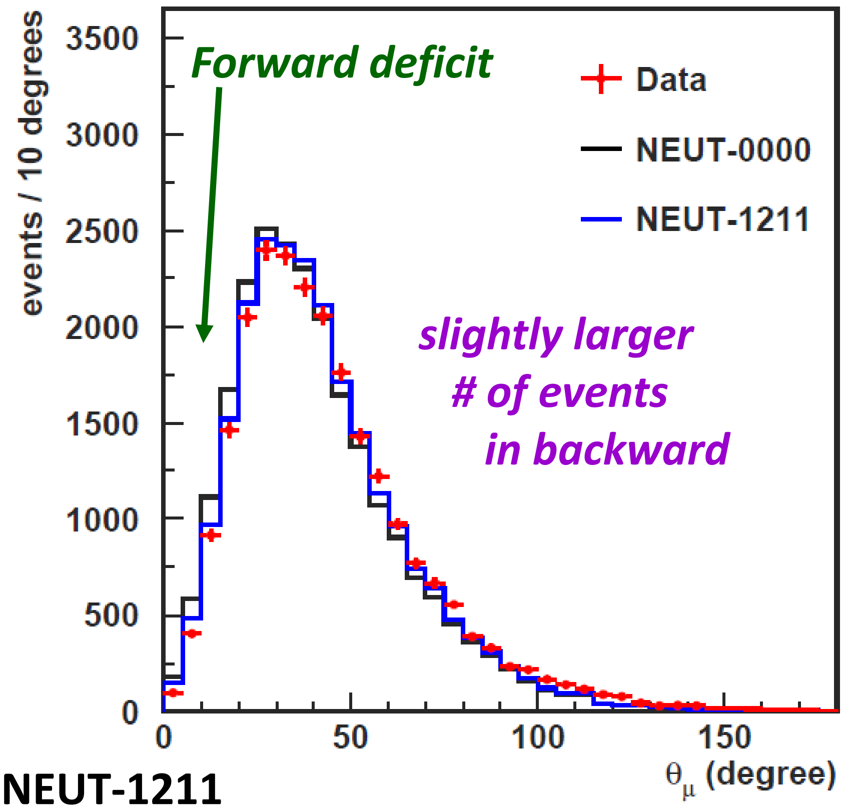
Miller, PRD 26, 537 (1982)

$Q^2[(GeV/c)^2]$

The K2K experiment

Comparison with K2K 1kt detector and simulation data

Direction of μ w.r.t. beam



NEUT-1211

M_A=1.1 GeV/c^2 for CCQE

M_A=1.2 GeV/c^2 for 1π

GRV94 with Bodek-Yang corr.

Coherent π by Marteau et.al.

Fully contained 1 ring μ-like events

NEUT-0000

M_A=1.0 GeV/c^2 for CCQE

M_A=1.0 GeV/c^2 for 1p

GRV94, Rein Sehgal coherent p

Less forward going μ

More backward going μ

Agreements was better if we increased M_A.

Also, need corrections on DIS parton distribution function (Suggested by Bodek and Yang) and suppression of CC Coherent π production.

Important to measure large angle scattering!

Charged current Quasi-elastic scattering

$M_A = 1.20 \pm 0.12$ GeV

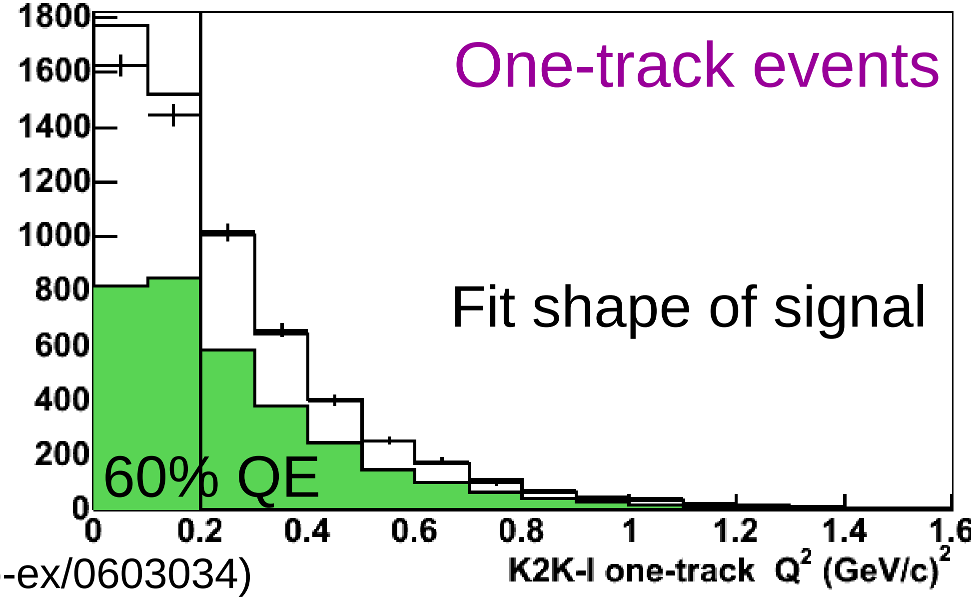
(χ^2 = 261/235 dof) shape only

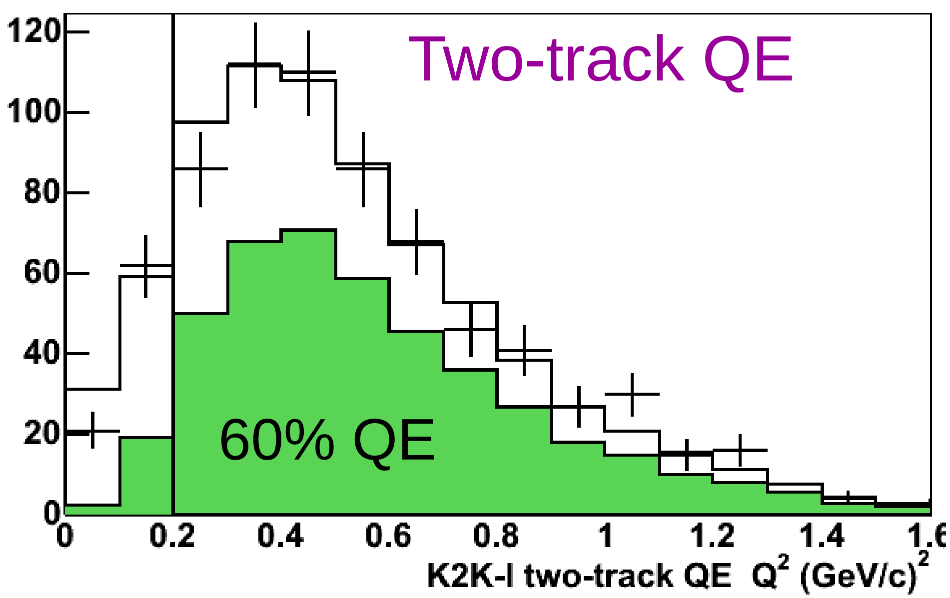
Most significant errors:

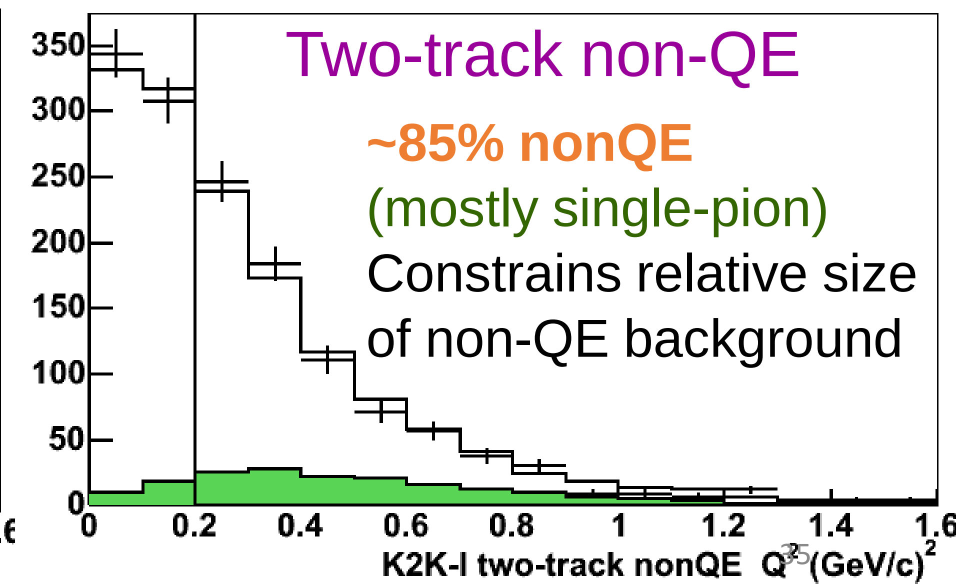
- Muon momentum scale 0.07
- Relative flux and normalization 0.06
- M_A 1π 0.03
- relative non-QE fraction 0.03
- Nuclear re-scattering 0.03
- Statistics only 0.03

R.Gran, E.Jeon, et al., accepted by PRD (hep-ex/0603034)

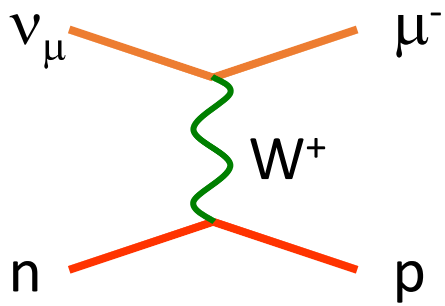
K2K SciFi M_A fit result







Charged current Quasi-elastic scattering

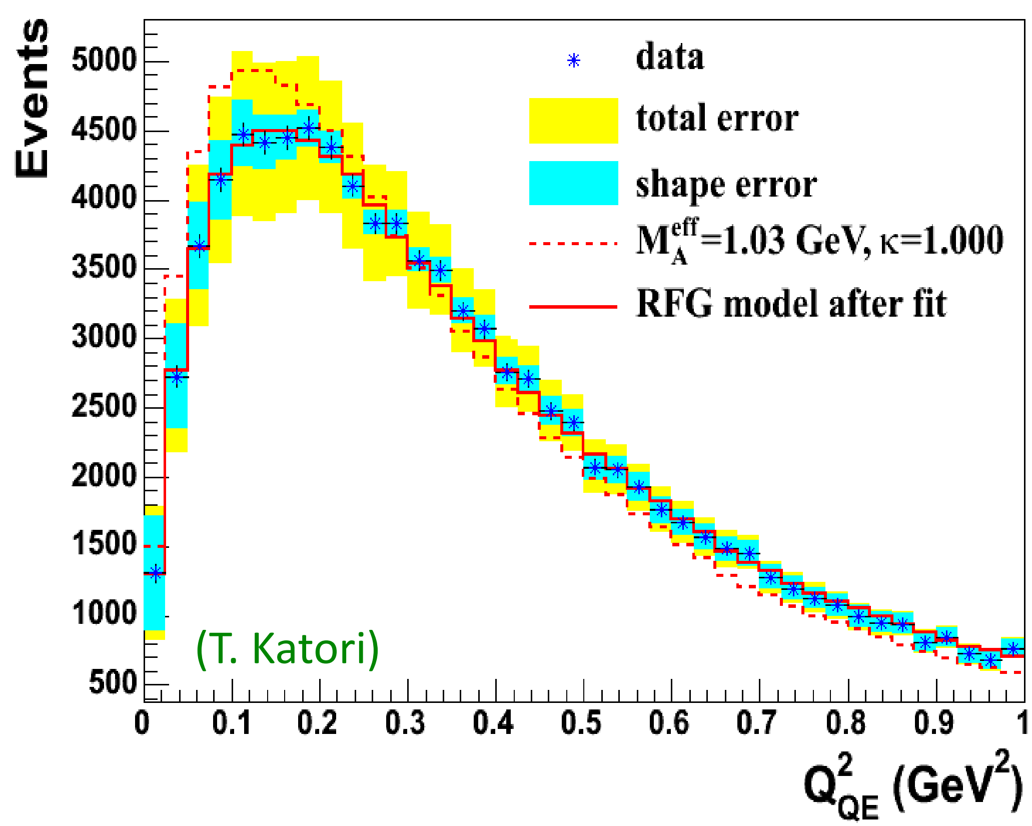


MiniBooNE

Axial vector form factor parameter M_A

$$F_A(Q^2) = \frac{g_A}{\left(1+Q^2/M_A^2\right)^2}$$

Need to be determined from the neutrino scattering data.



M_A=1.35 ± 0.17 GeV

- **World avg.**

  M_A=1.02 ± 0.17 GeV

- **K2K SciFi** (^{16}O, Q^2>0.2)

  Phys. Rev. **D74**, 052002 (2006)

  M_A=1.20 ± 0.12 GeV

- **K2K SciBar** (^{12}C, Q^2>0.2)

  M_A=1.14 ± 0.11 GeV

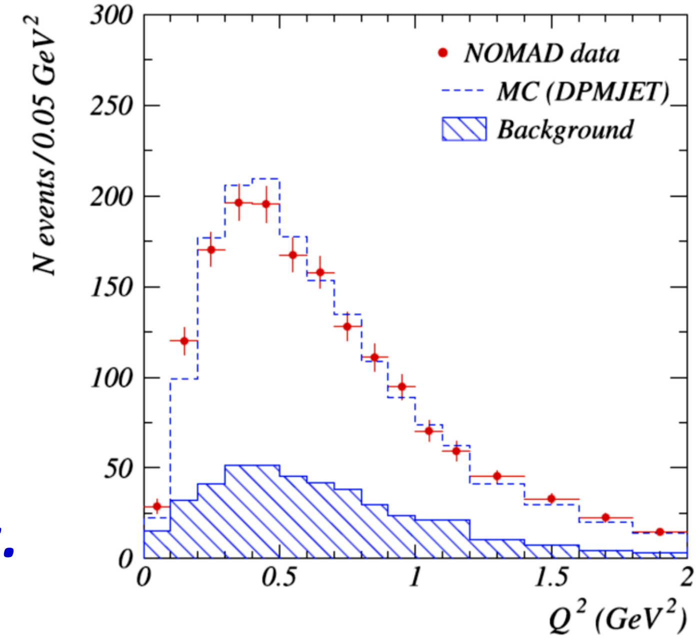
Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

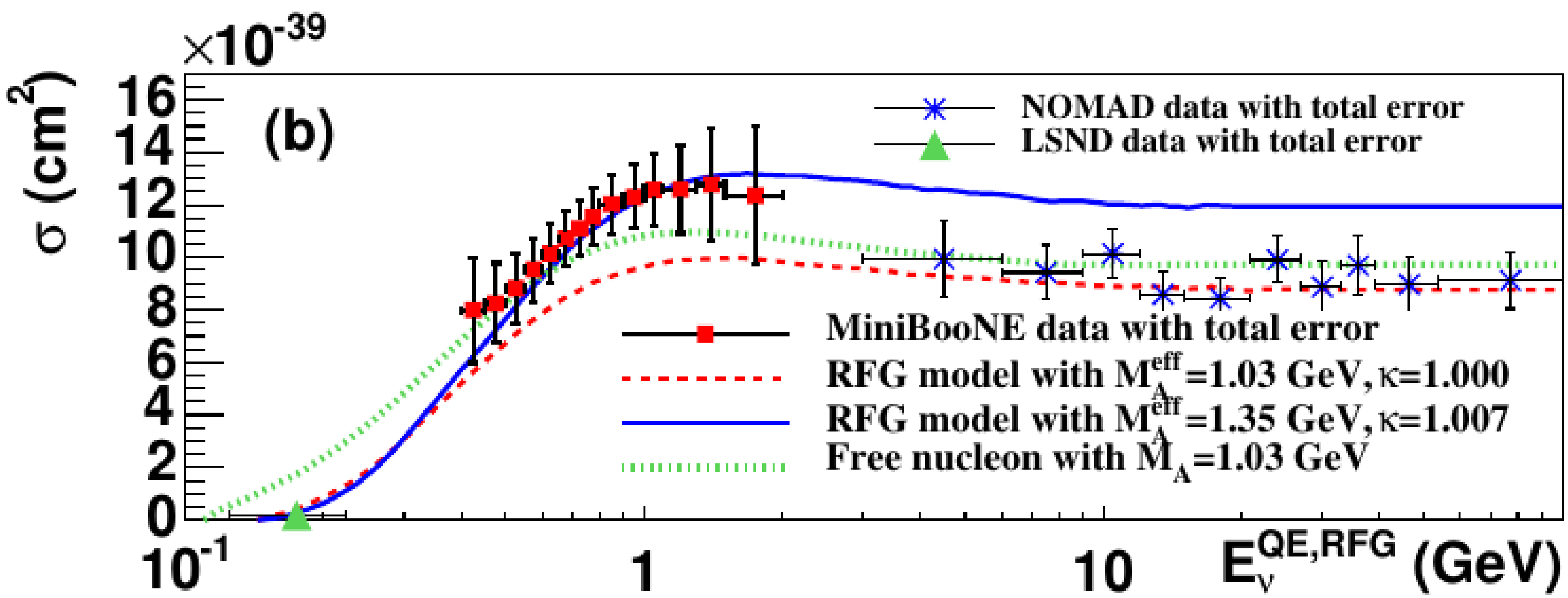
NOMAD experiment

Carbon target, $\langle E_\nu \rangle \sim 24$ GeV

$$M_A(\nu) = \mathbf{1.06} \pm 0.02(stat.)$$
$$\pm 0.06\ (syst.)\ \text{GeV/c}^2$$
$$M_A(\bar{\nu}) = \mathbf{1.06} \pm 0.07(stat.)$$
$$\pm 0.10\ (syst.)\ \text{GeV/c}^2$$

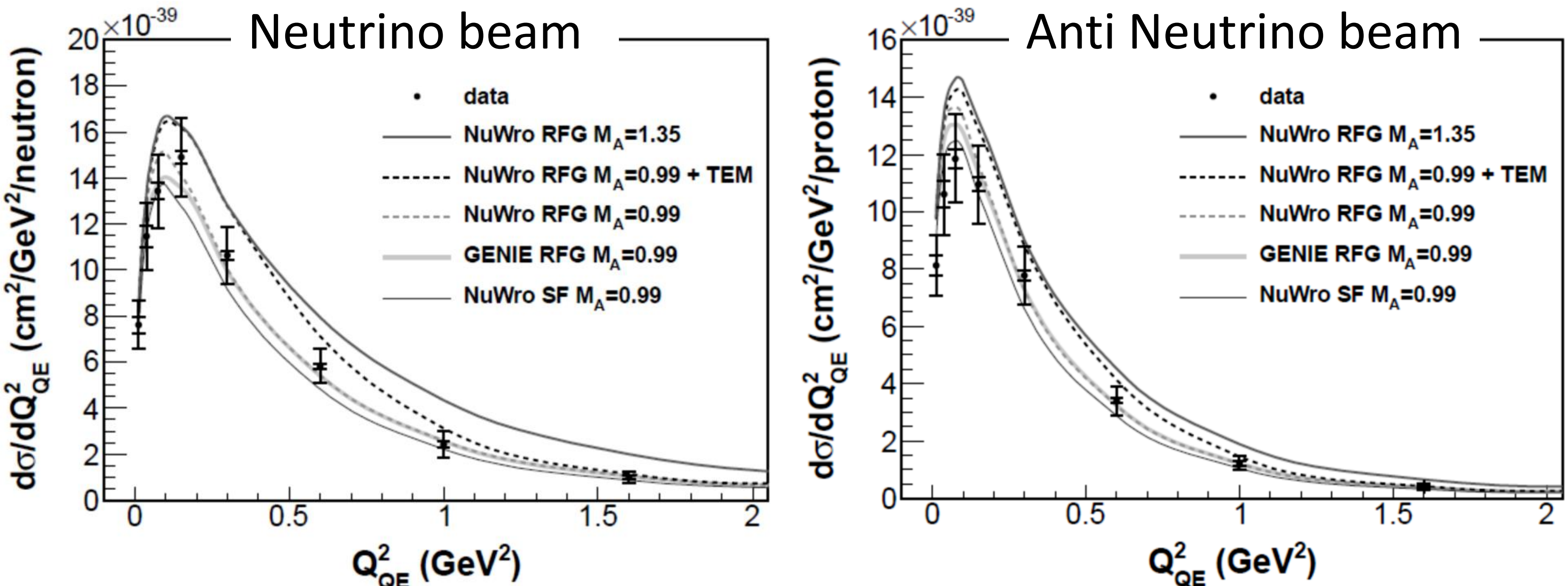
Consistent with Bubble chamber results.





Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

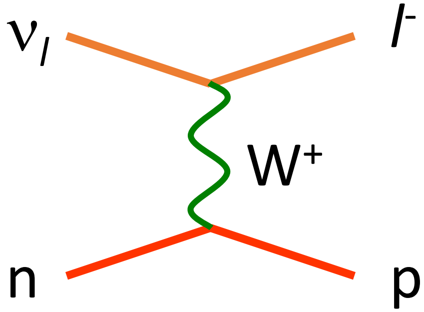
MINERνA Experiment $< E_\nu > \sim 3.5$ GeV



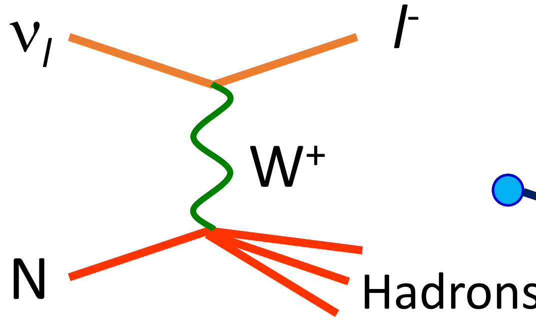
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

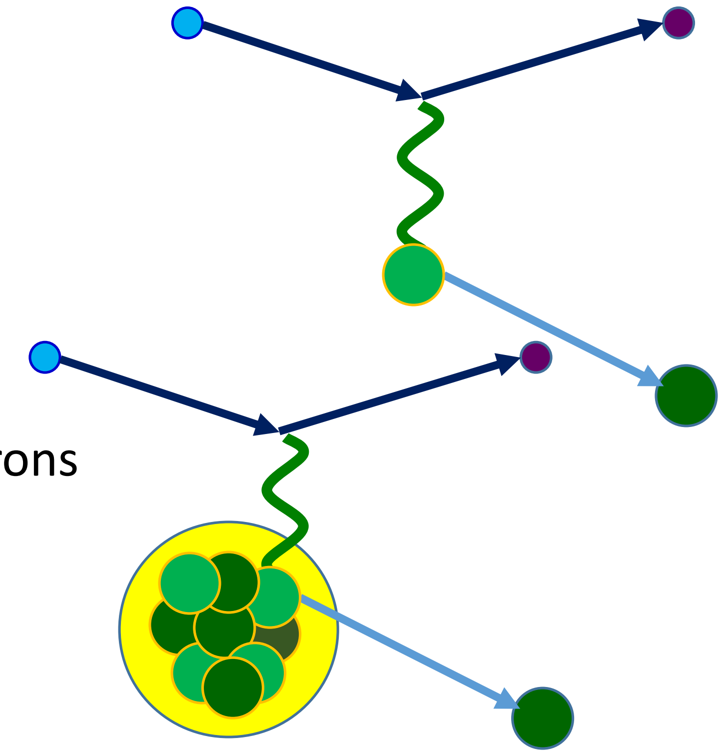
Simple relativistic Fermi Gas model M_A = 0.99 GeV/c^2
did not give the best fit result. Need some modification.

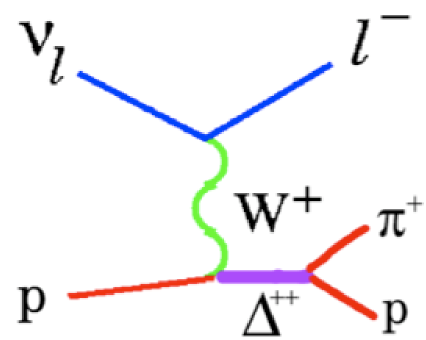


ν_l
l^-
W^+
n
p

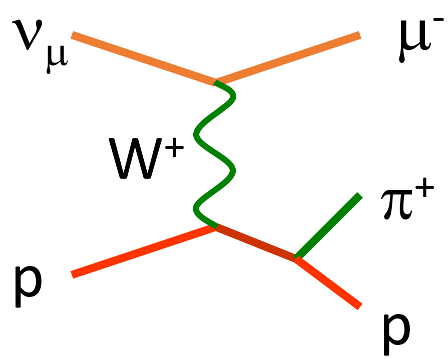


ν_l
l^-
W^+
N
Hadrons

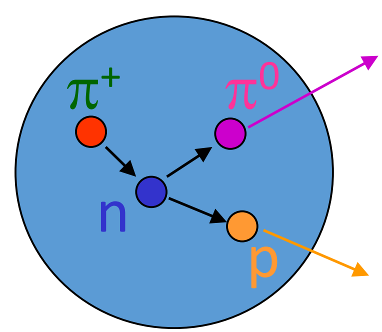




ν_l
l^-
W^+
π^+
p
Δ^{++}
p



ν_μ
μ^-
W^+
π^+
p
p



π^+
π^0
n
p