Overview of neutrino-nucleus interactions
(From an experimentalist's point of view)

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Neutrino-nucleon interactions above 100 MeV

Charged current quasi-elastic scattering (CCQE)

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

Neutral current elastic scattering

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

Single meson productions

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

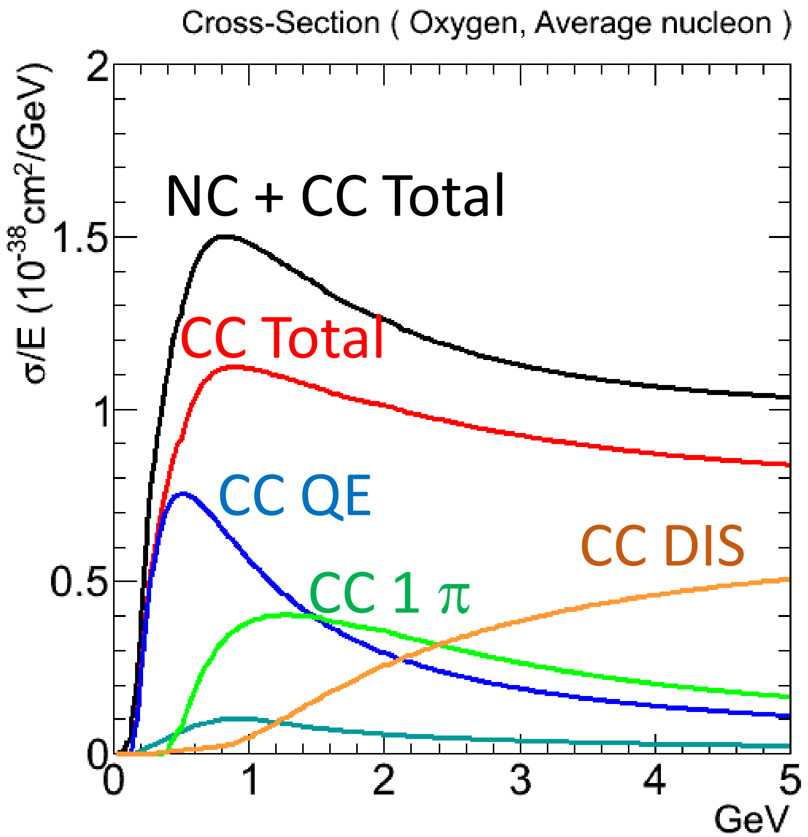
Single photon productions

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

(radiative decay of resonance)

Deep (/ shallow) inelastic scattering

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



- 1GeV ~ a few GeV

  CCQE, CC1π and CCDIS have similar cross-sections

- above several GeV

  CCDIS dominates

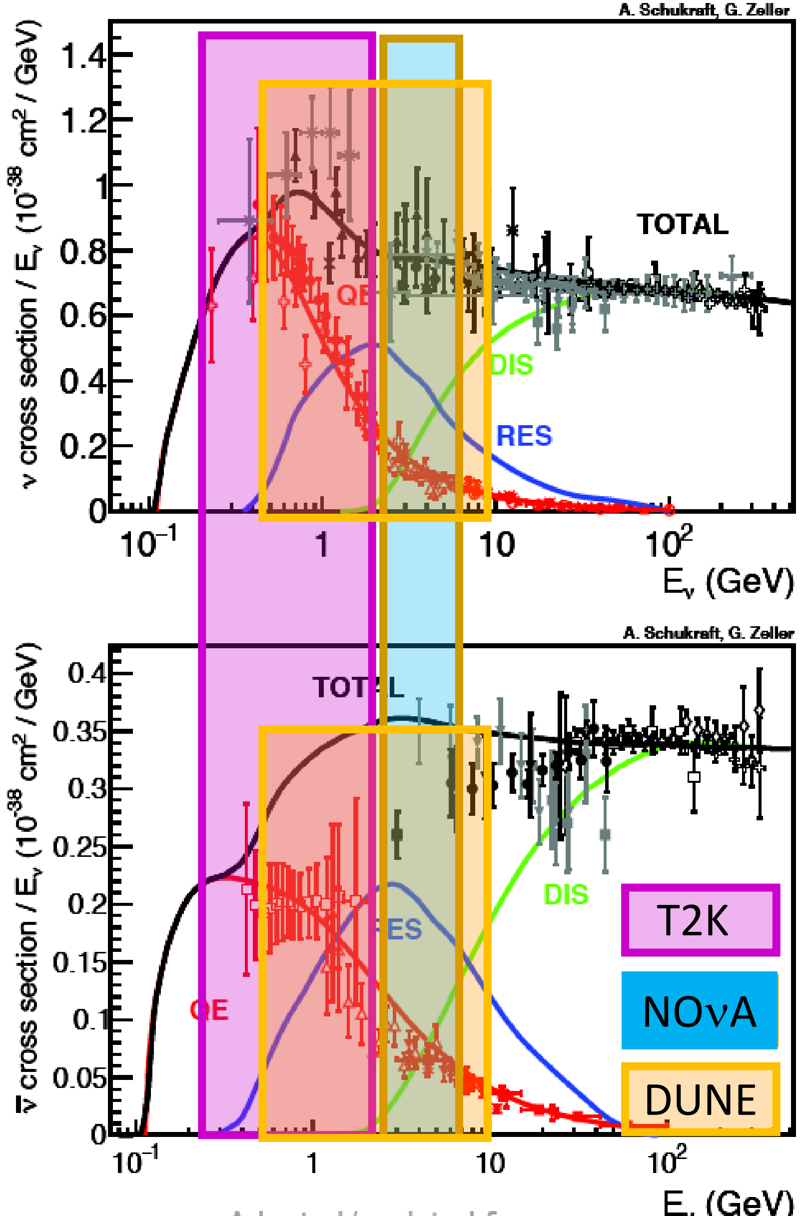
Introduction

Current and next generation neutrino oscillation experiments use a few hundreds to ~10 GeV neutrinos.

These experiments are using "nuclear" targets.

T2K	CH,H_2O (near)
	H_2O (far)
NOνA	CH (near and far)
DUNE	Argon (far)

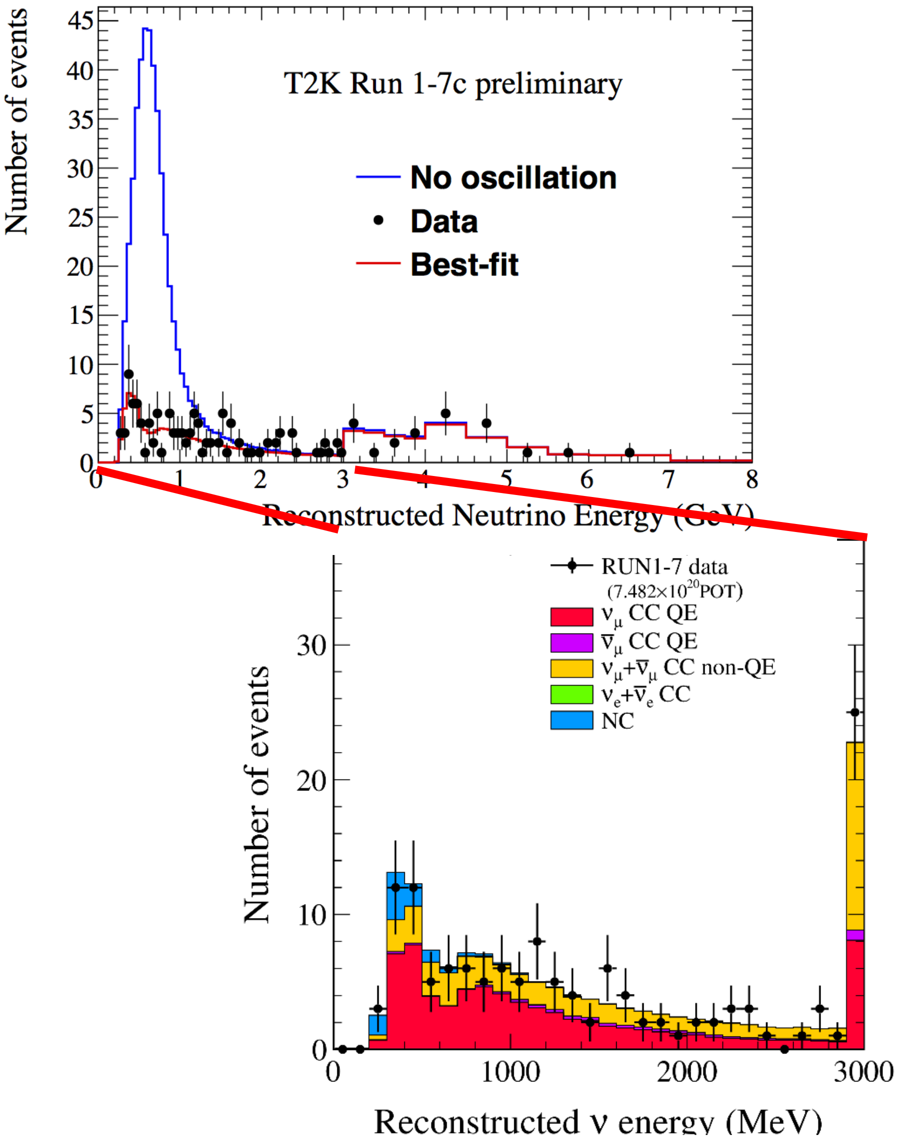
In these experiments, systematic uncertainty is required to be less than a few % to achieve their physics goals.

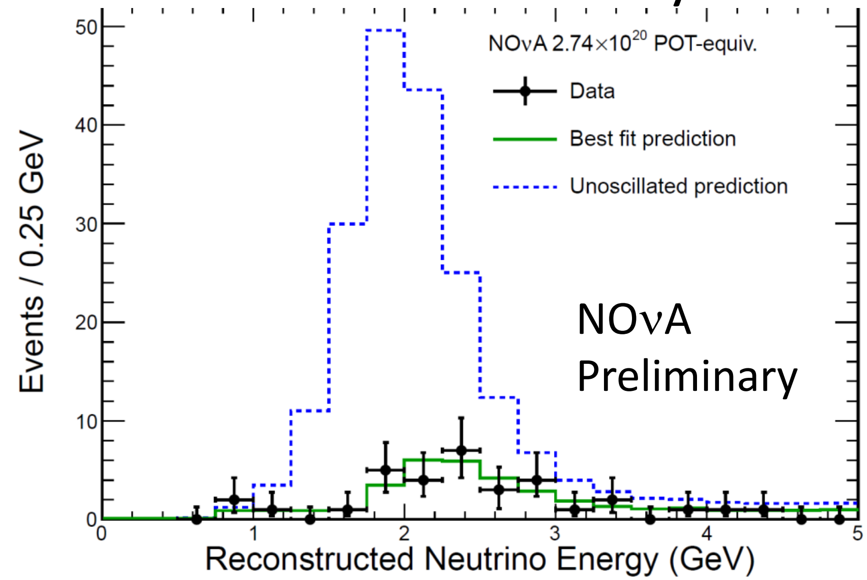


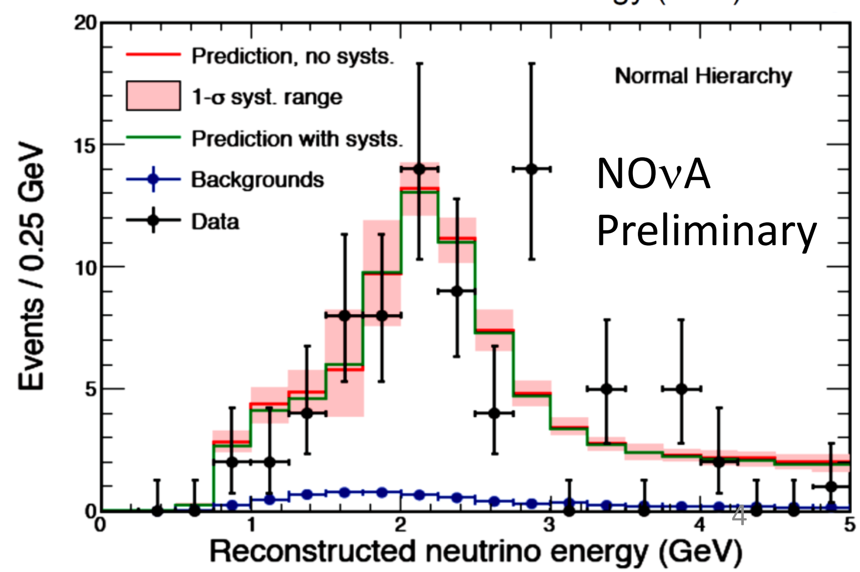
Adapted/updated from
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Introduction

Precise understandings of neutrino – nucleus interaction are crucial in the oscillation analysis.







Introduction

Uncertainties from neutrino – nucleus interaction
may be one of the major source of the systematic errors
in the (near) future neutrino oscillation experiments.

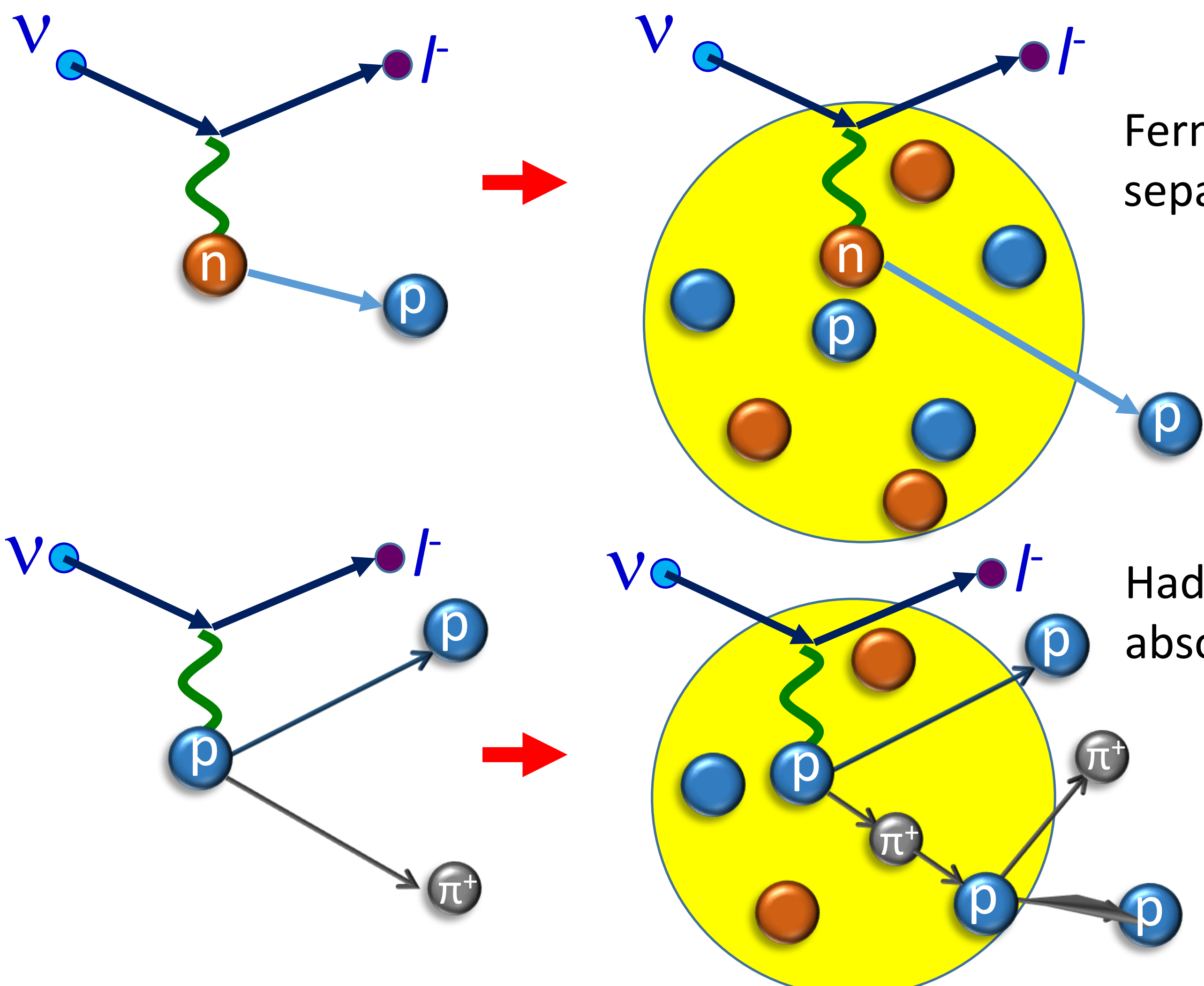
Systematic error of T2K ν_e appearance search
(# of candidate events)

Source of uncertainty	**ν 1 ring e**	**$\bar{\nu}$ 1 ring e**
SK detector	2.4%	3.1%
SK final state & secondary interactions	2.5%	2.5%
Flux & ν interactions constrained by ND280	2.9%	3.2%
NC 1γ production ($\nu + N \rightarrow \nu + N' + \gamma$)	1.4%	3.0%
Cross-section ratio (ν_μ to ν_e)	2.7%	1.5%
Other neutral current interactions	0.2%	0.3%
Total	5.5%	6.2%

Introduction

From neutrino-nucleon interactions to neutrino-nucleus interactions

Necessary to take into account various corrections in the medium



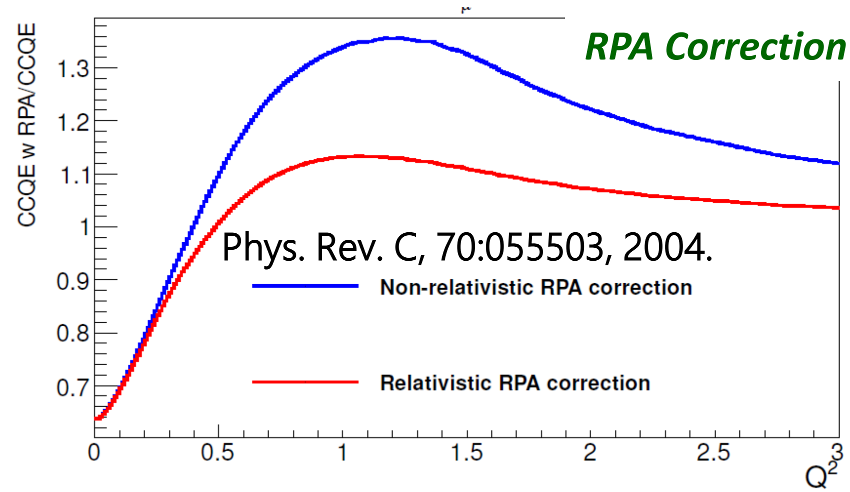
Fermi motion,
separation energy etc..

Hadron re-scattering,
absorption etc..

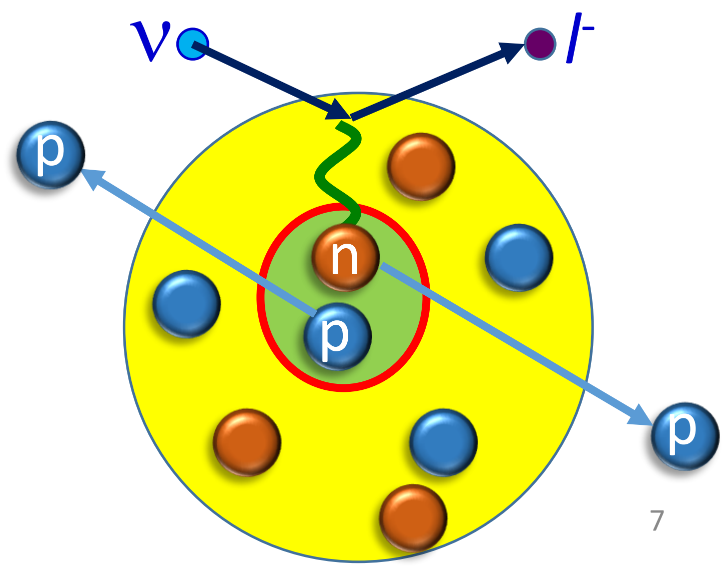
Introduction

From neutrino-nucleon interactions to neutrino-nucleus interactions

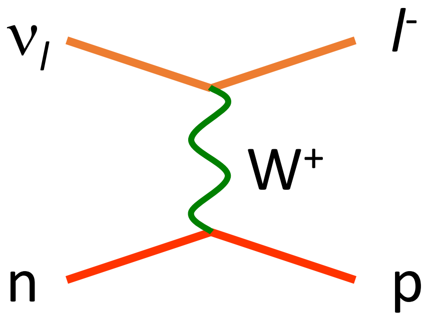
The presence of strongly interacting nucleons in nucleus may change the he weak interaction strength.
(Estimated with RPA corrections)



Interaction with “correlated” pair of nucleons in nucleus seems to be non-negligible.

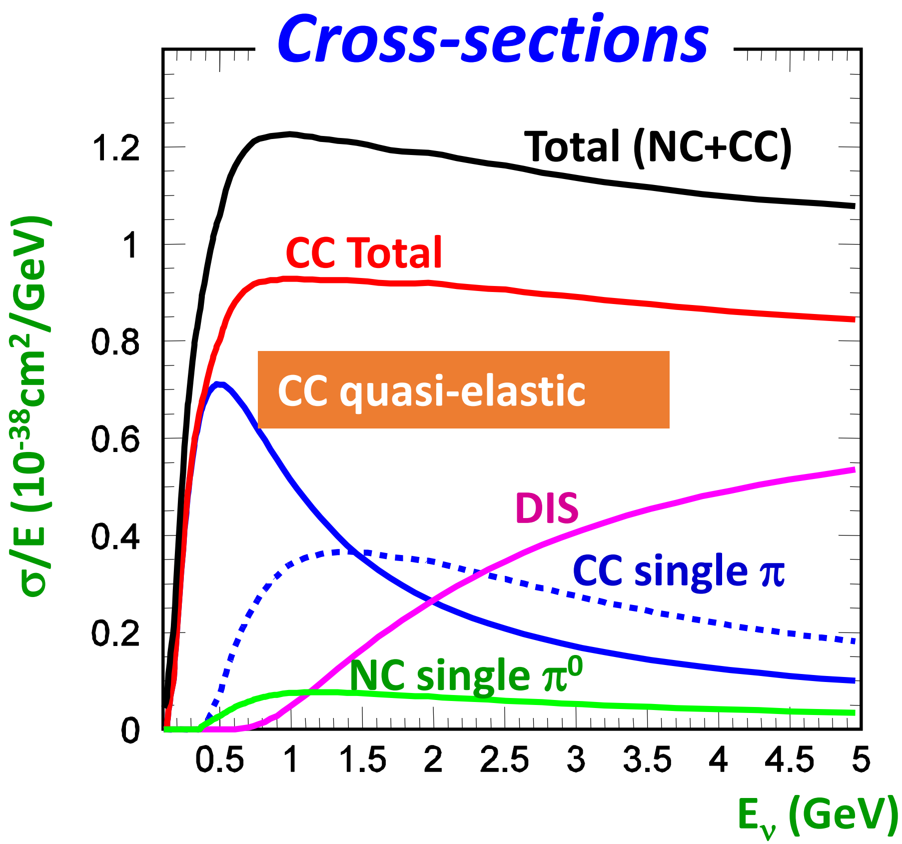


Charged current quasi-elastic scattering $\nu + n \rightarrow l^{-} + p$

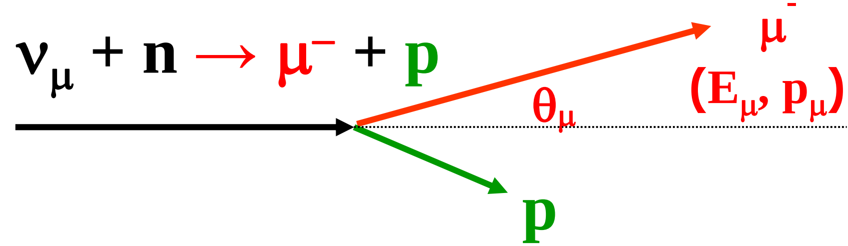


Major interaction in the low energy region
(~ 1 GeV)

2 body reaction
~ Possible to reconstruct neutrino energy
if one knows the direction of incoming n
and can assume
the target nucleon is at rest



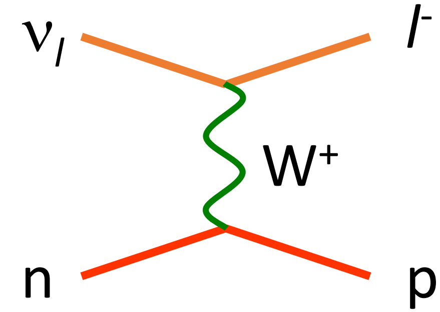
$\nu_\mu + n \rightarrow \mu^- + p$



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Unfortunately, we don't know
from where atmospheric neutrinos
are coming from

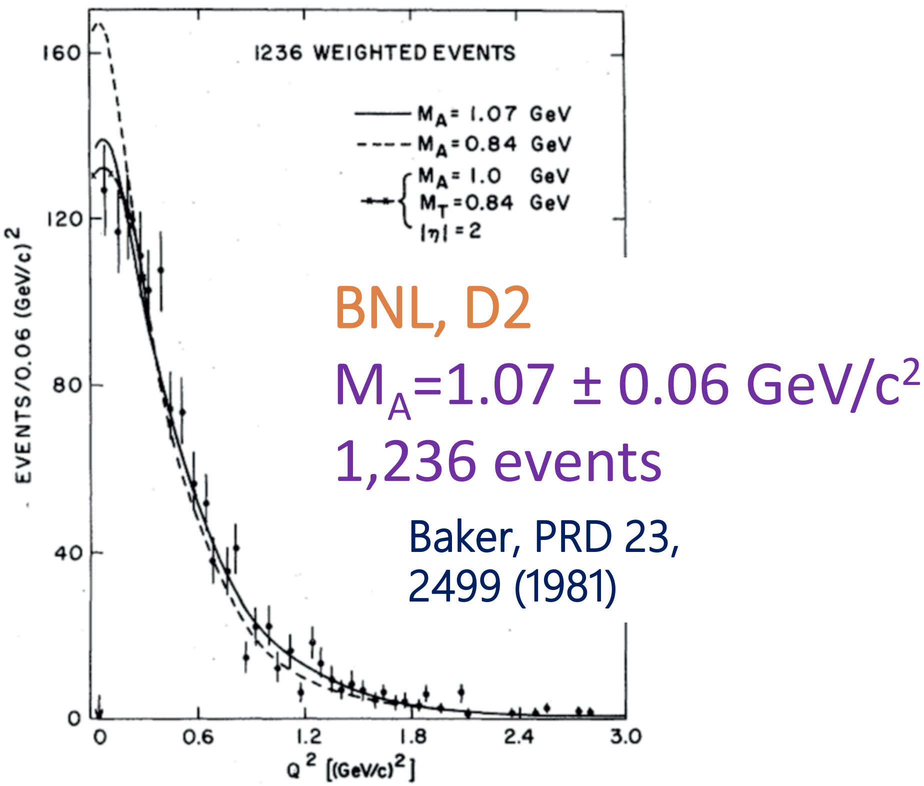
Charged current quasi-elastic scattering

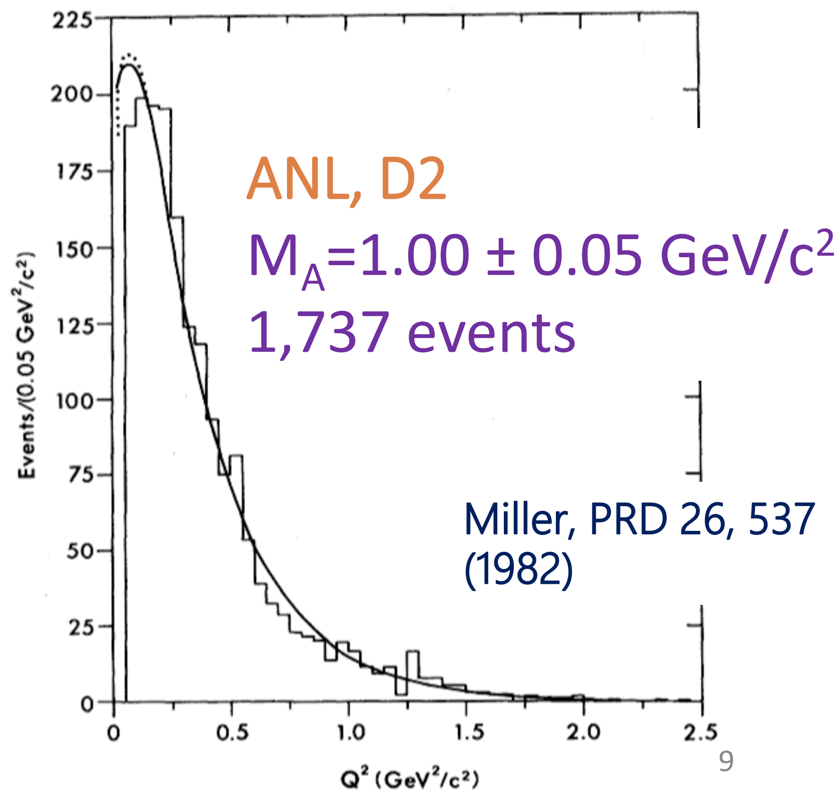


Axial vector form factor has to be determined to calculate neutrino-nucleon CCQE cross-sections.

Dipole form ($F_A(q^2) = F_A\,(0) \times \left(1 - \frac{q^2}{M_A^2}\right)^{-2}$) is used.

M_A was obtained to be ~1.05 GeV/c^2 (D (^{2}H) bubble chamber exp.)





Charged current quasi-elastic scattering

Extension from nucleon scattering to nucleus scattering:

simple Fermi-gas model has been widely used.

(R. Smith and E. Moniz, Nucl. Phys. B43, 605 (1972)).

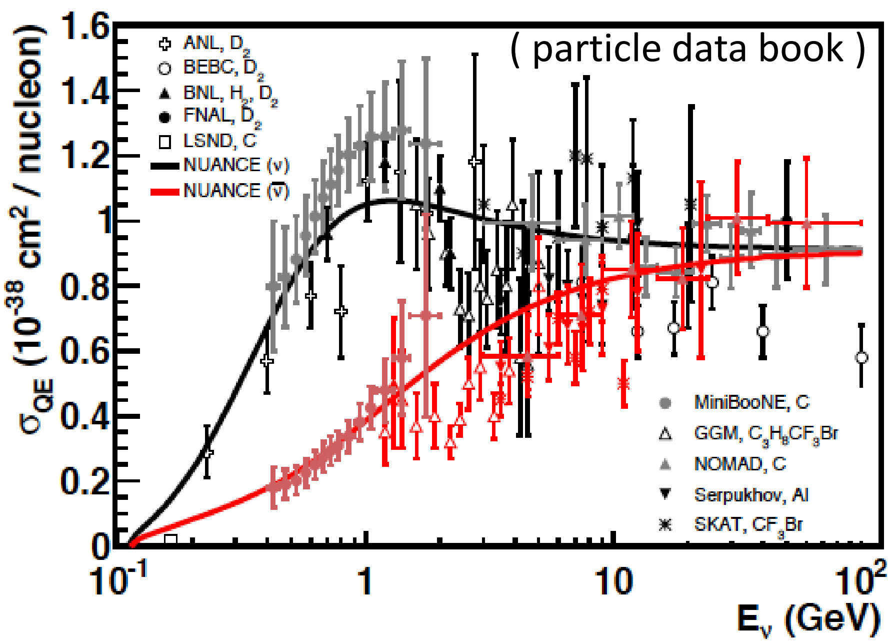
Since K2K (~2000), several disagreements are found:

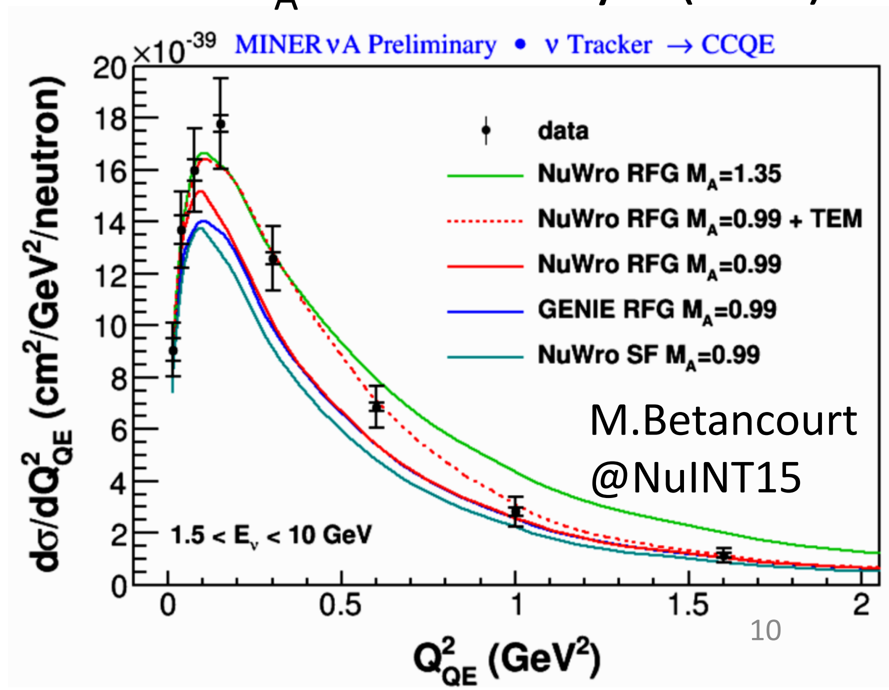
1) Forward going muon is larger than data

~ larger suppression in small q^2

2) Larger # of "CCQE-like" events are observed

One solution is to increase M_A for CCQE by O(20%).





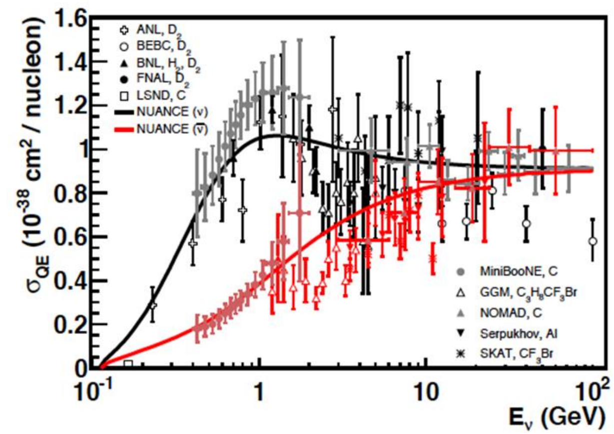
Charged current quasi-elastic scattering and related

Several possible explanations (solutions) have been proposed.

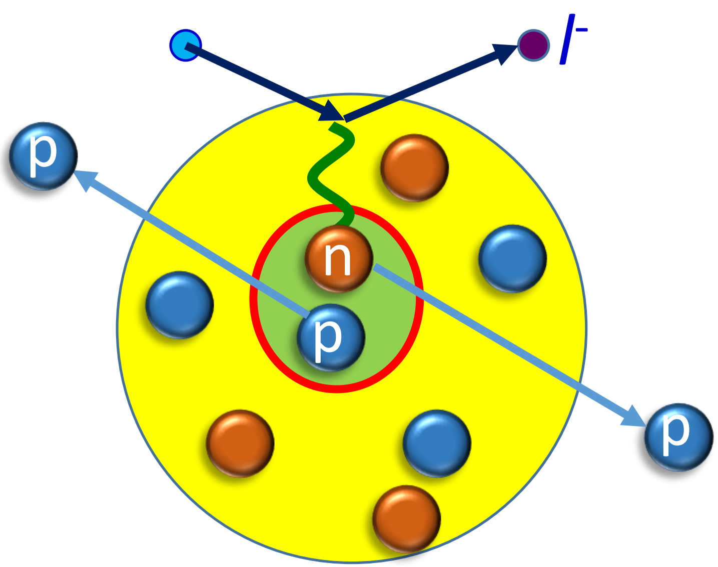
- Dipole form factor is not appropriate.
- Simple Fermi-gas is not appropriate
- Correlation (RPA correction etc.)

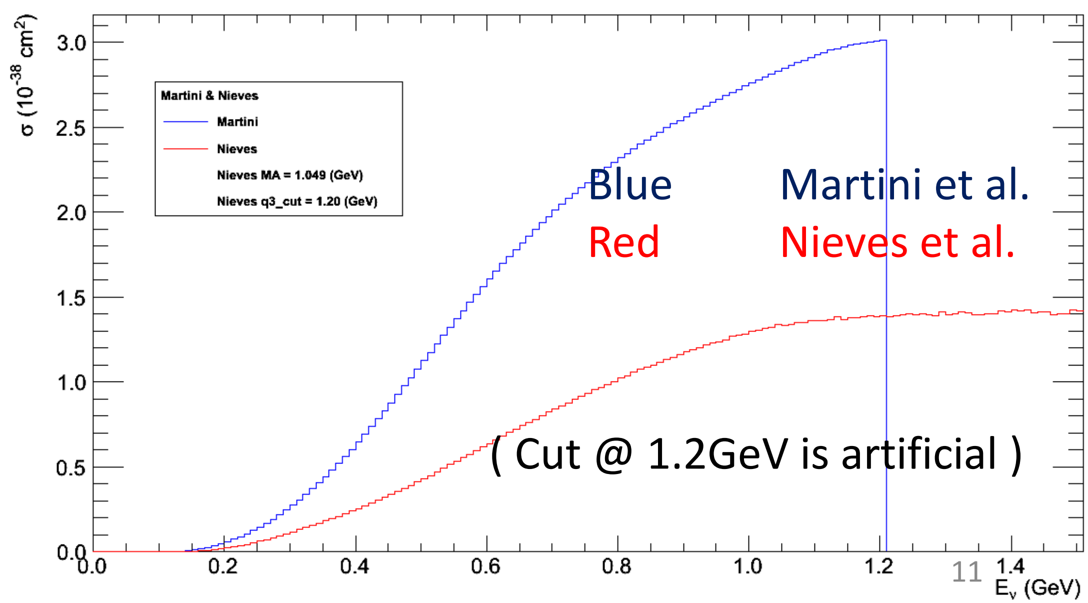
  need to be taken into account.
- Scattering with bound nucleon pair

  need to be taken into account.

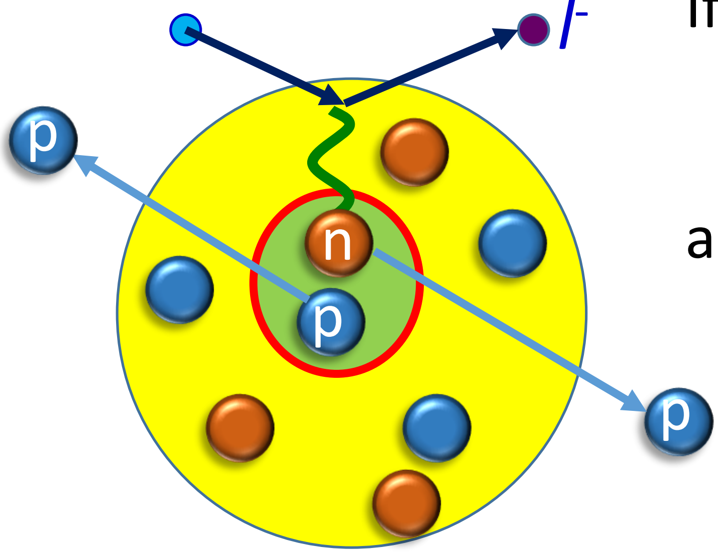


2 nucleon scattering : Comparison of two calculations



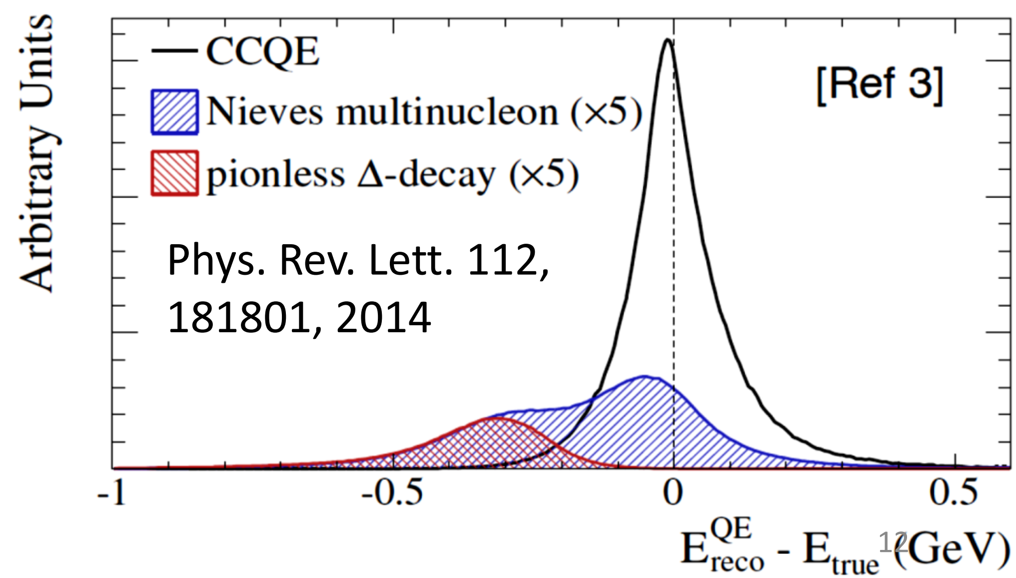


Charged current quasi-elastic scattering-like interaction



If the discrepancies between CCQE prediction and CCQE-like observed events, are caused by bound nucleon scattering, reconstructed energy is shifted for those events.

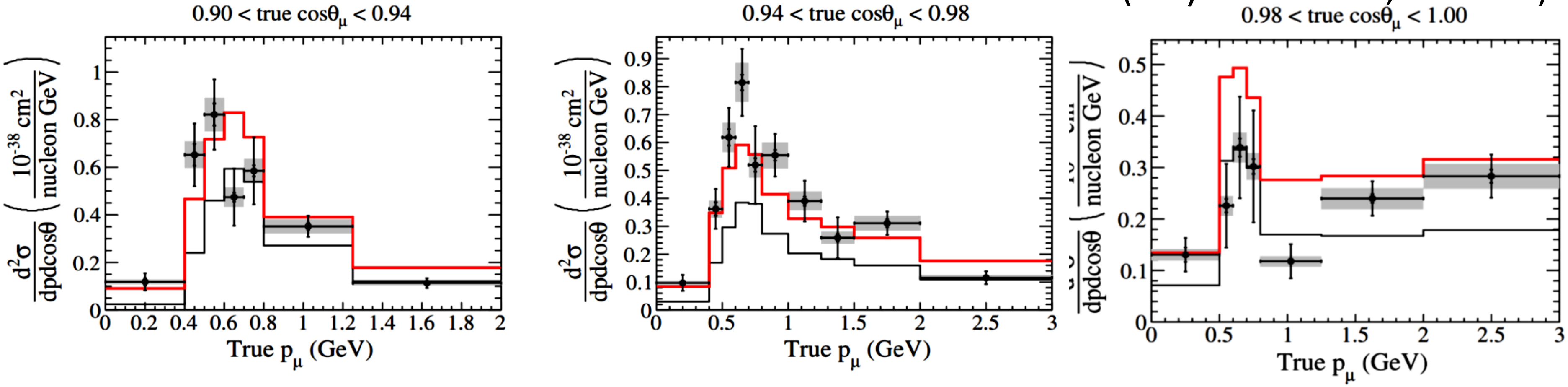
The fraction of these events is less than ~ 20% of true CCQE (if we assume naive model) but the effects may be visible in precise experiments.



Charged current quasi-elastic scattering and related

Indication of “additional” interaction other than CCQE
Data sample without pions prefer to have
“additional” interactions.

T2K ND280 data (Phys. Rev. D 93, 112012)



Red With 2p2h (multi-nucleon) interaction
Black Without 2p2h interaction

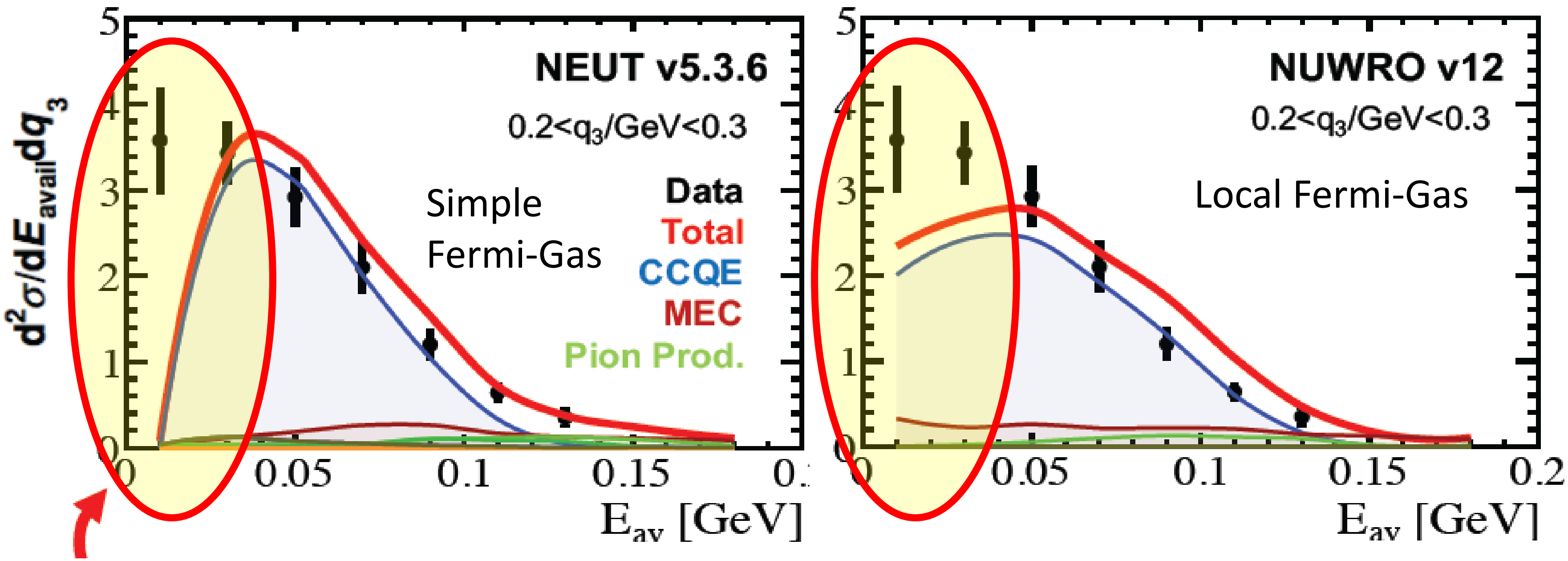
However, it is difficult to select or reject proposed models because the recent detectors are rather coarse and not optimized for this kind of studies.
(i.e. Insufficient resolution and/or efficiency of low momentum hadrons etc.)

Charged current quasi-elastic scattering and related

MINERνA Low q_3 sample indicates that
the existence of low momentum protons.

Available energy = (Visible) hadron energy distribution

Patrick Stowell @ NuFact16 Data from PRL 116, 071802 (2016)

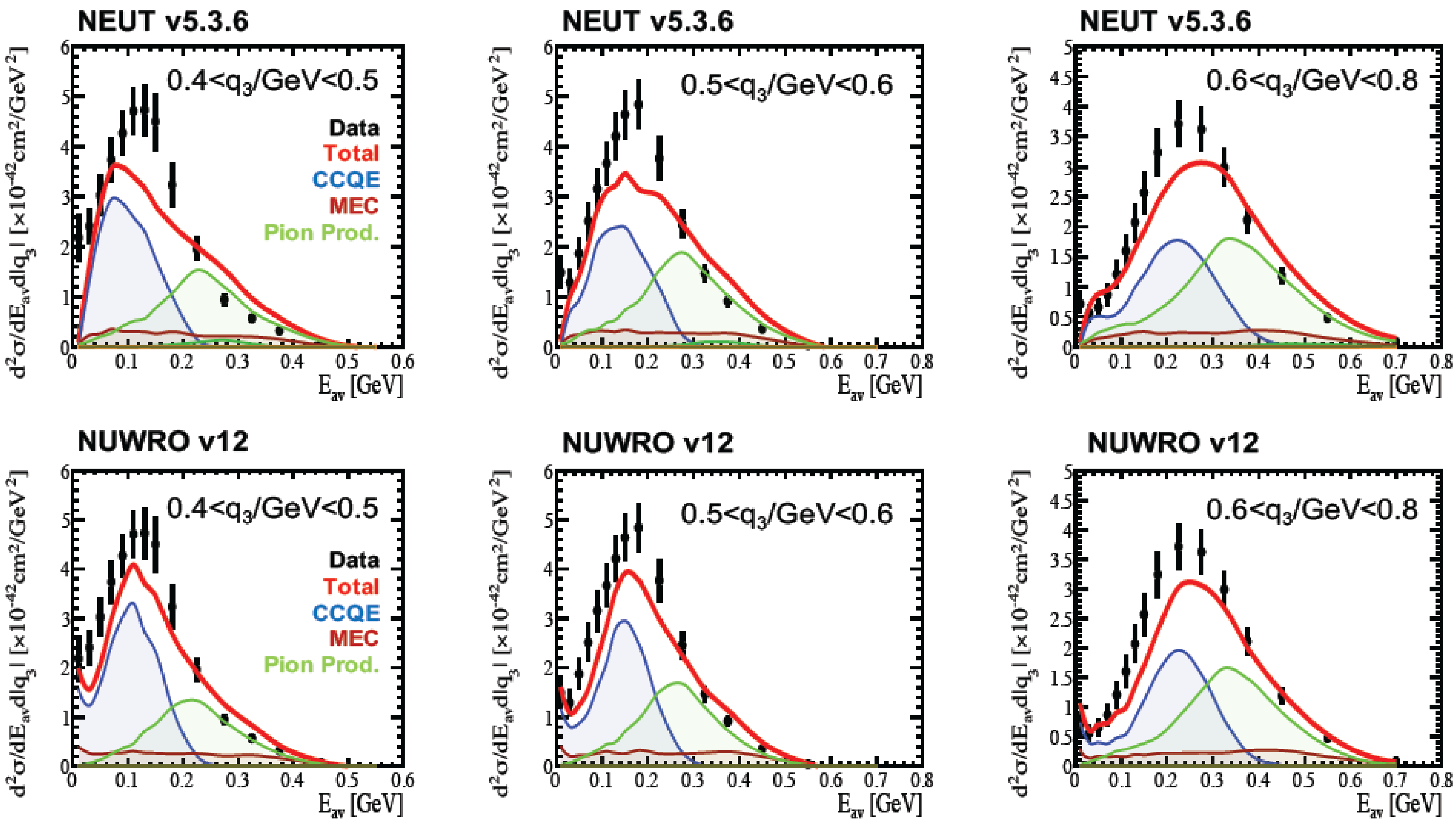


Limitation of uniform nucleus model ("Global Fermi gas model")
is clearly seen.

Necessary to use "Local Fermi Gas" or further sophisticated models.

Charged current quasi-elastic scattering and related

Current implementation of hadrons from 2p2h
(multi-nucleon scattering) simulation code
seems not sufficient to explain the discrepancy.

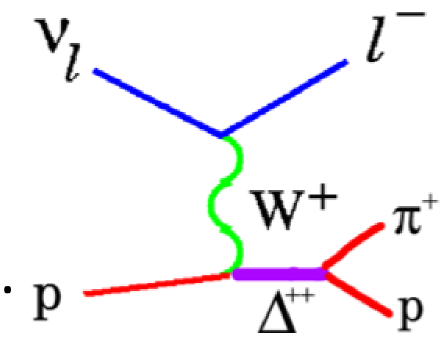


MINERνA Low q_3 sample

Patrick Stowell @ NuFact16

Single π production via resonance

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



W or Z excites nucleon and resonance is produced.

Then, resonance decay into pion and nucleon.

$\nu + N \rightarrow l + \Delta\ (N^*)$

$\quad \longrightarrow \Delta(N^*) \rightarrow \pi + N'$

Most of the simulation program uses the model

based on D.Rein, and L.M.Sehgal. (Ann. of Phys. 133(1981))

Which is based on "Relativistic harmonic oscillator model"

by Feynman, Kislinger and Ravndal.

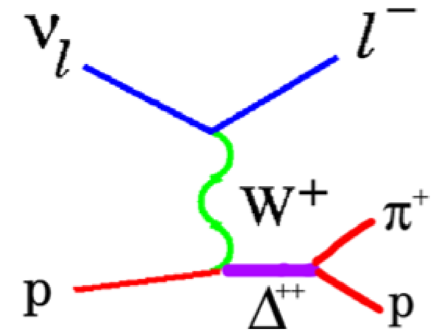
(Feynman et al. Phys. Rev. D3 (1971) 2706)

Their model take into account the resonances below 2 GeV.

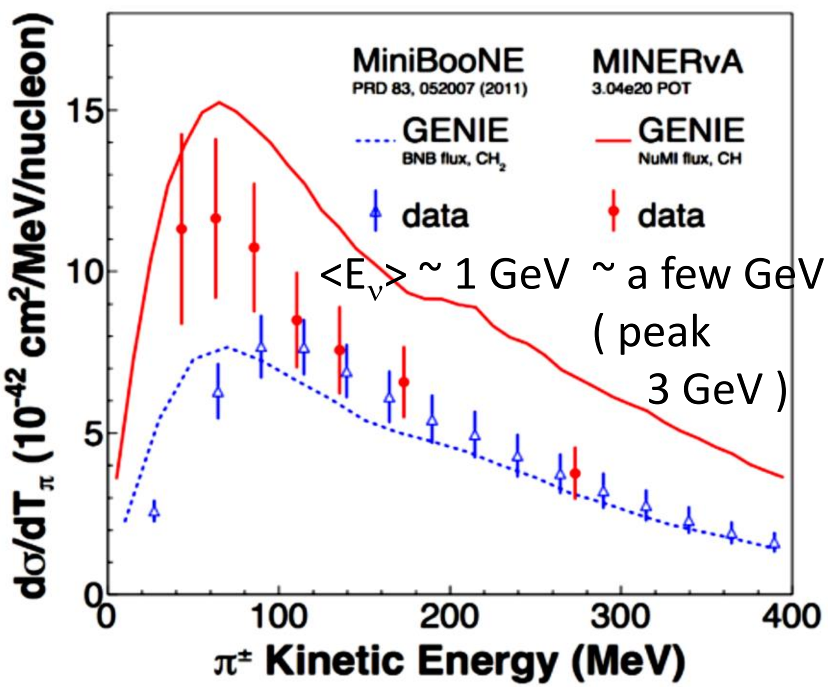
(Actual selection of the resonances in the simulation programs depends on the implementation.)

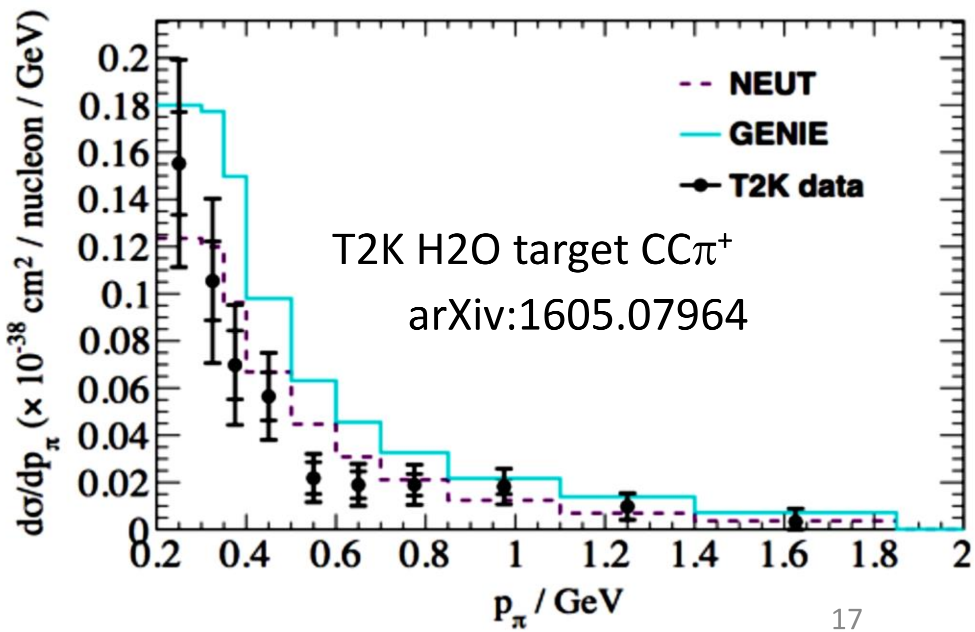
Single π production via resonance

If the beam is neutrino,
charged current π^+ is the dominant interaction
and most of πs are coming from Δ(1232).
$(\nu + p \rightarrow l^- + \Delta \rightarrow l^- + p + \pi^+)$

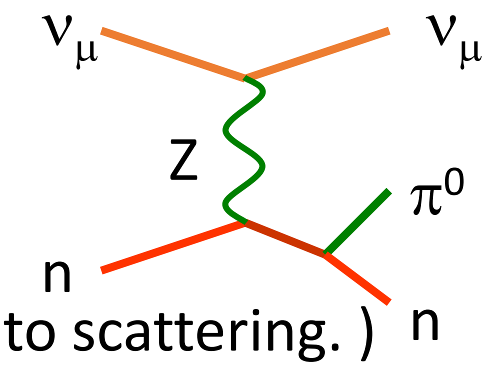


π from this interaction easily interacts with nucleon,
both inside of nucleus and also in the detector
-> π re-interactions has to be understood.



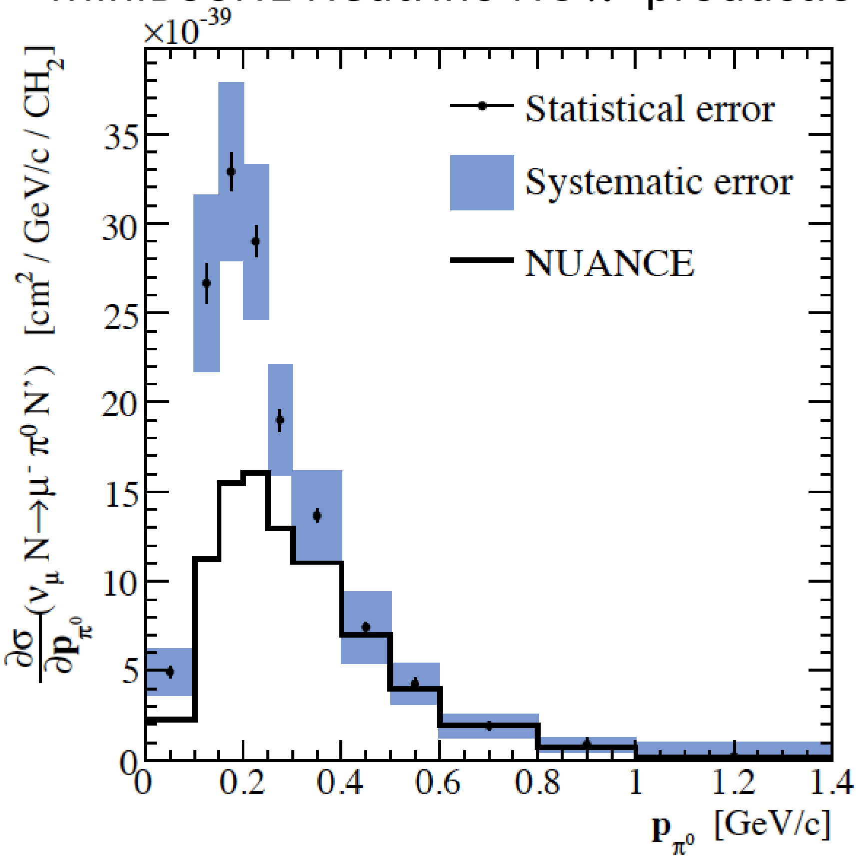


Single π production via resonance

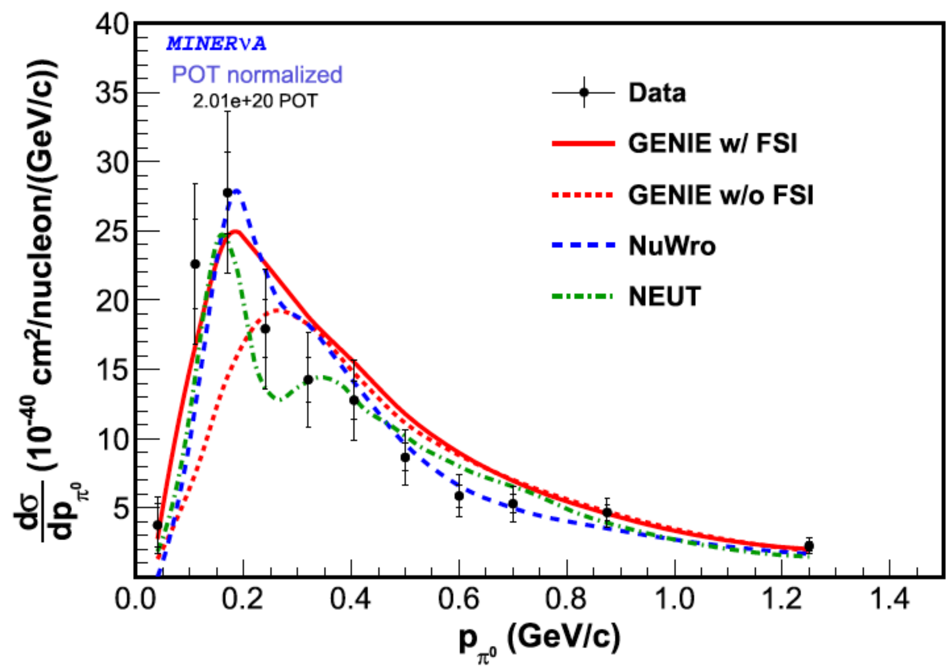


NC π^0 production channel is interesting
because the rescattering effect in water
is different from π^+ channel.
(Charge exchange σ from $\pi^\pm$ is smaller compared to scattering.)

MiniBooNE Neutrino NC π^0 production



MINERνA anti-neutrino NC π^0 production

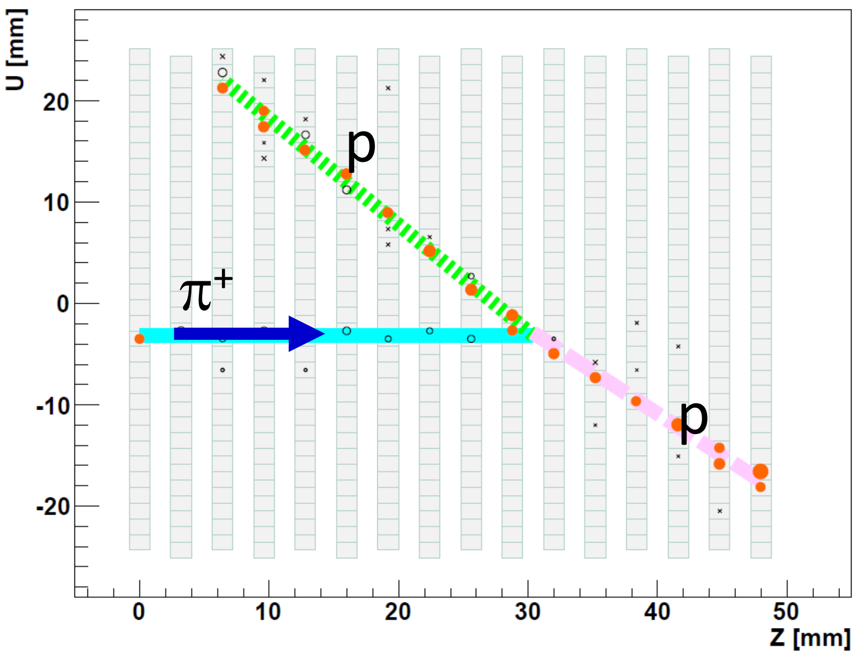


Nuclear effects ~ pion interaction in nucleus

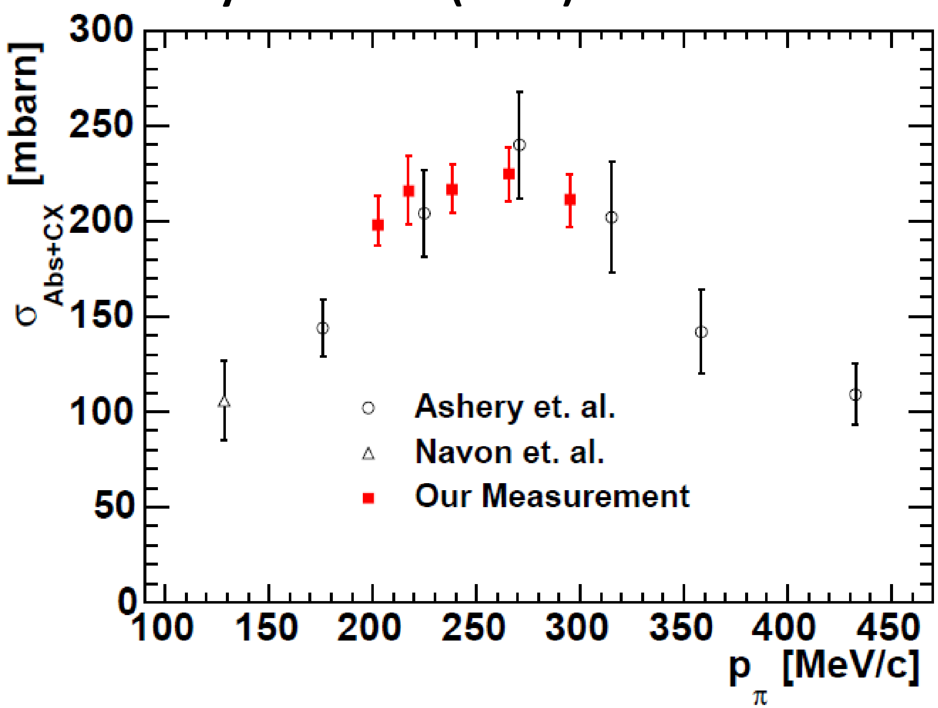
DUET experiments measured

absorption + charge-exchange cross-sections.

Absorption candidate events



Phys.Rev. C92 (2015) 035205



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.

Shallow ~ Deep inelastic scatterings $\nu + N \rightarrow l + \text{hadrons}$

Dominant interaction in the high energy region (> several GeV)

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

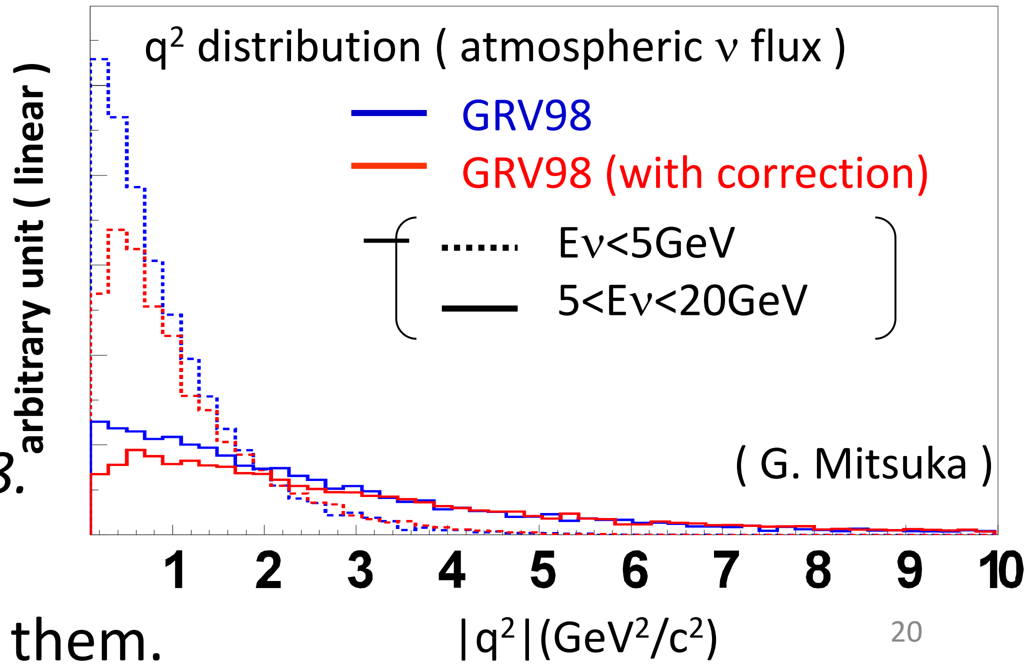
We need to know F2 or xF3 (structure functions).

These could be calculated using parton distribution functions, which are extracted from experimental data.

Differential cross-section ($d\sigma/dq^2$) has peak in small $|q^2|$.

However, usual PDFs are not valid for small $|q^2|$.
(GRV98, $|q^2| > 0.8\ \mathrm{GeV}^2$)

Need special treatment.
Bodek & Yang suggested corrections for GRV98.



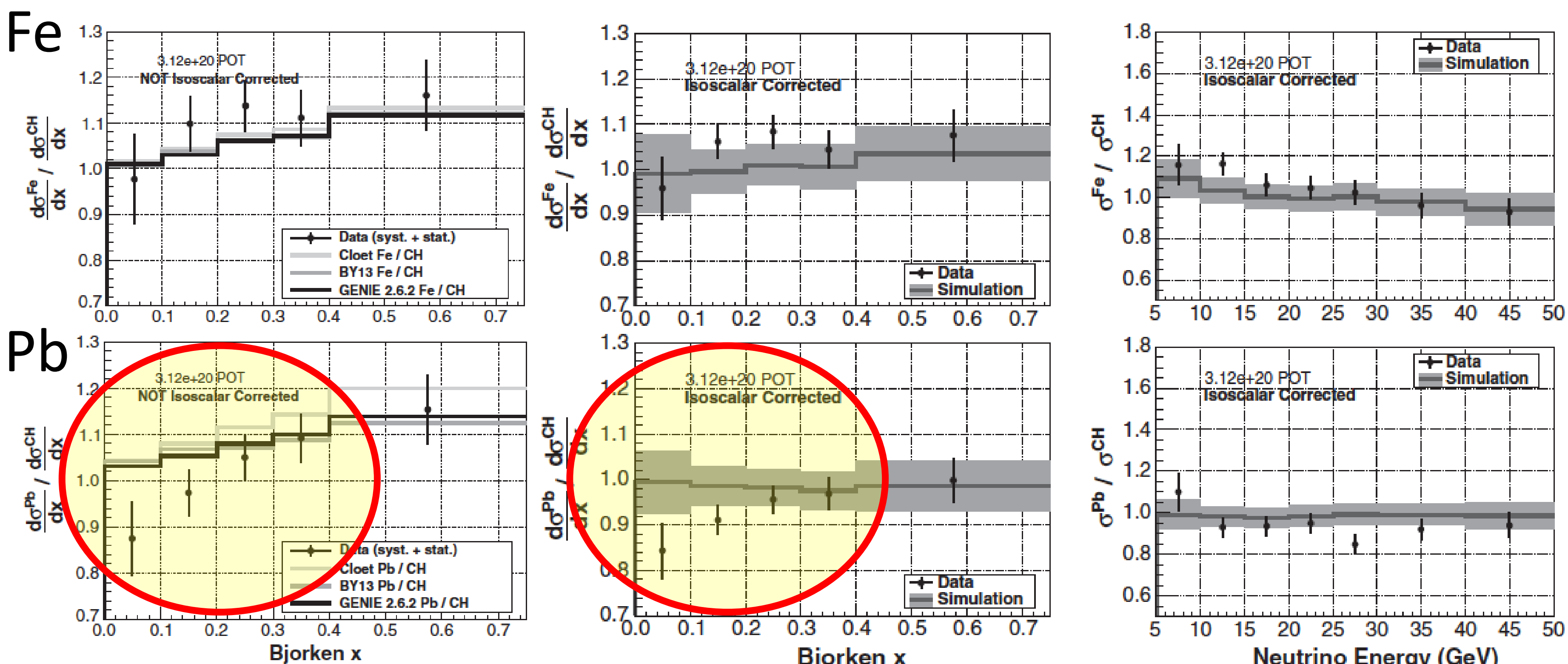
There are several new PDFs.
We need new correction for them.

Shallow ~ Deep inelastic scatterings

Even for the deep-inelastic scatterings,
it is necessary to take into account
nuclear dependence especially the target is heavy.

(Several groups started “nuclear” parton distribution functions recently.)

MINERνA PHYSICAL REVIEW D 93, 071101(R)



Necessary data for further understanding

Lack of precise low momentum hadron information

~ difficult to identify the interaction

= difficult to select model or tune the parameters

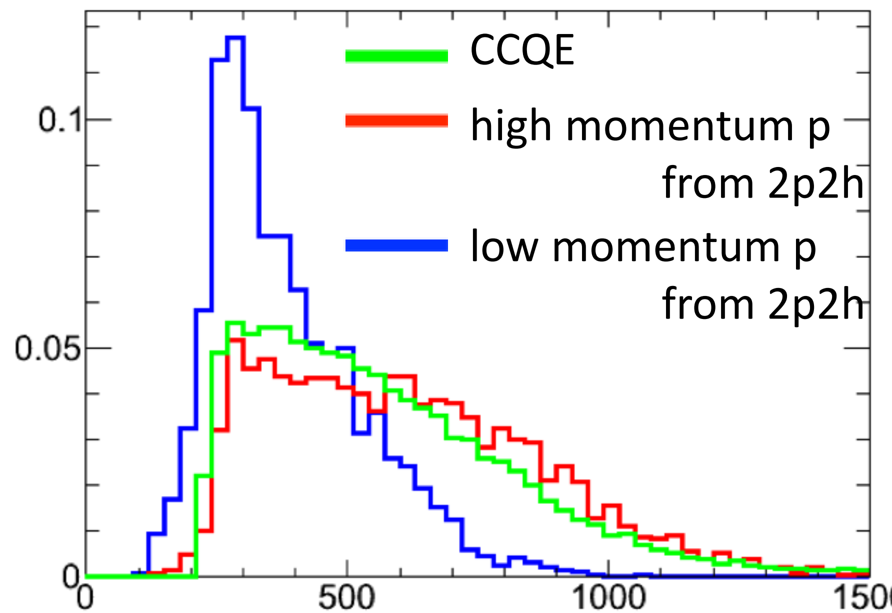
Threshold of proton need to be ~ 300MeV/c at least.

Also, directional information is necessary

to study the re-scattering of hadrons

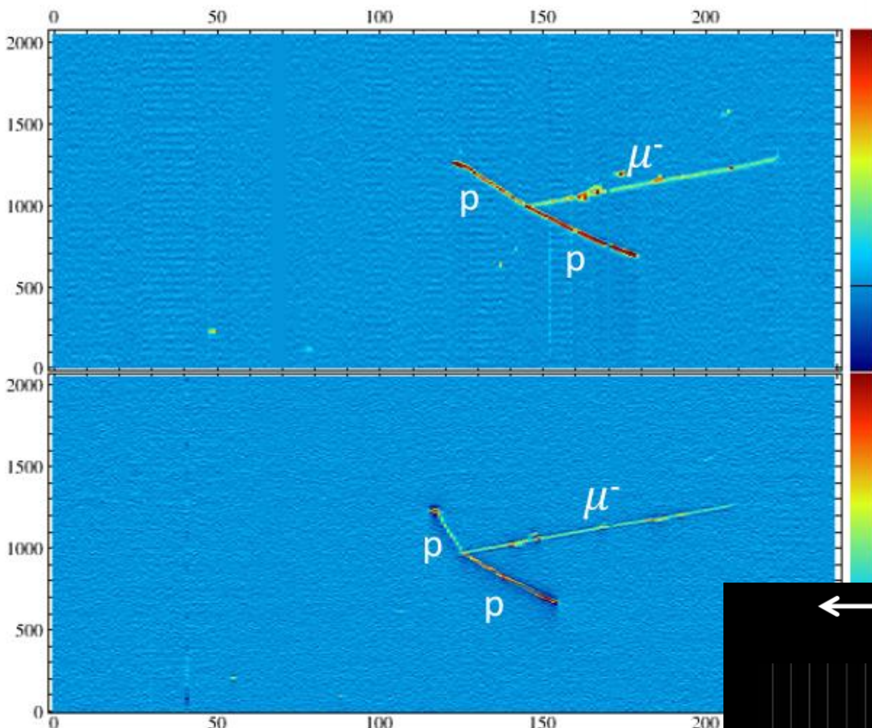
and correlation of the nucleons.

Momentum distribution of protons
from CCQE and 2p2h CCQE-like events
Global Fermi-gas for CCQE and
simple uncorrelated hadron model
for 2p2h are used to make the plot.
If "correlated" nucleon pair model is used,
distribution of momenta
will be quite different.



Necessary data for further understanding

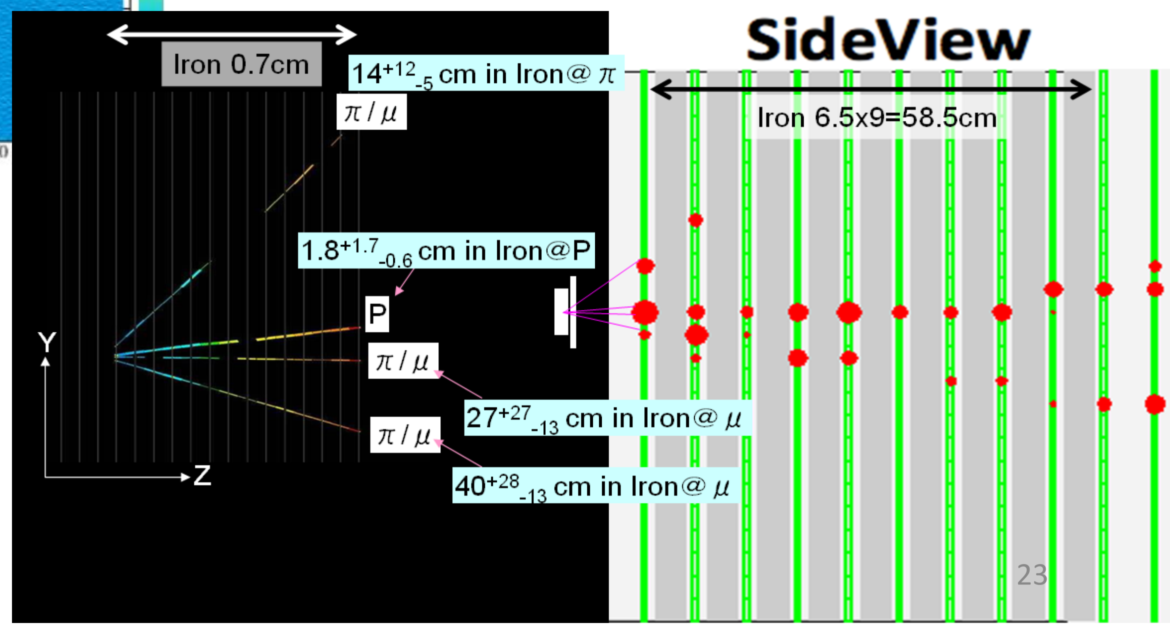
Need low momentum hadron track information



ArgoNeuT observed several 2 proton knockout events

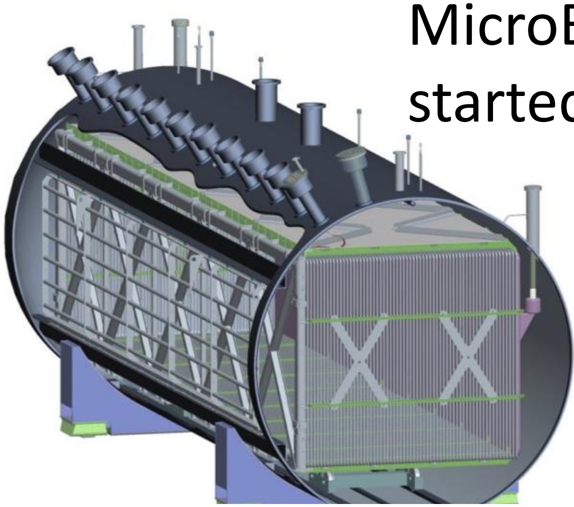
~ Signature of multi-nucleon scattering or nucleon emission after π absorption

T-60 Emulsion detector (with Iron target) observed CC events @ J-PARC ν beamline

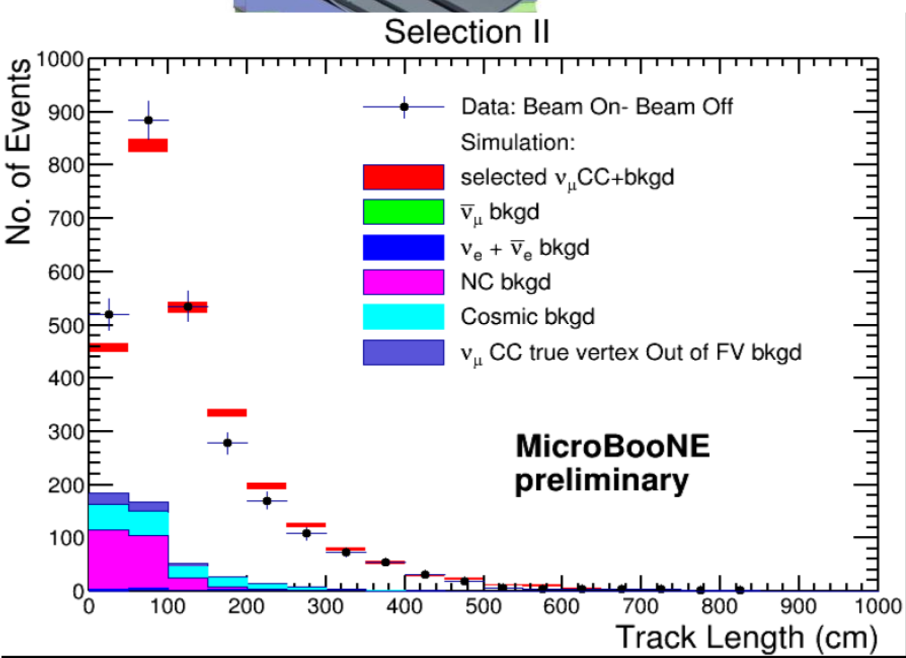


Necessary data for further understanding

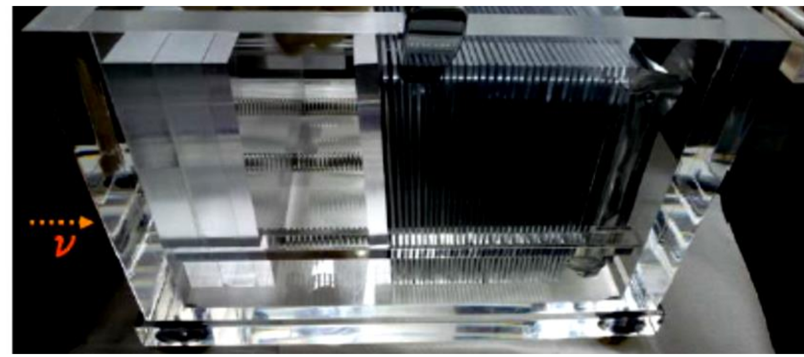
Need low momentum hadron track information

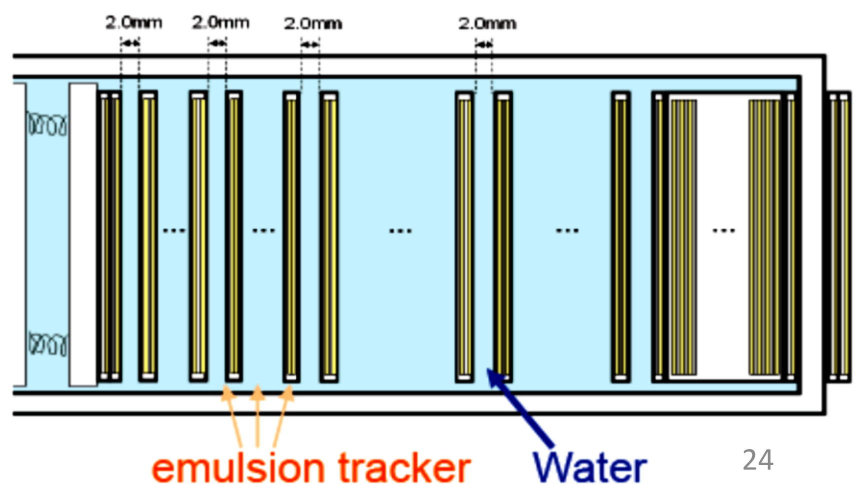


MicroBooNE has started taking data



Experiment with Water/Carbon + Emulsion film detector is planned at J-PARC





Summary

Since 2000, several experiments have studied various
neutrino-nucleus interactions.
The results are not always consistent
with previous “simple” assumptions and models.

The next generation neutrino oscillation experiments require
more precise understanding of neutrino-nucleus interaction.

New theoretical works help to understand the observations.
However, current (existing) data seem not sufficient
(accurate / precise) to select the best descriptions.

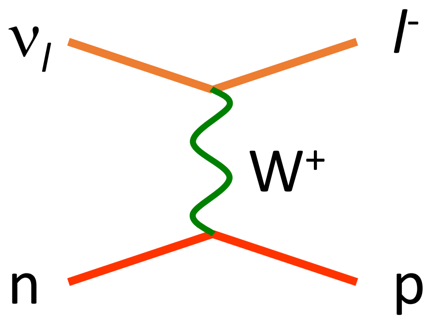
Recently started and currently planned high precision experiments
are essential to reduce the systematic uncertainties.

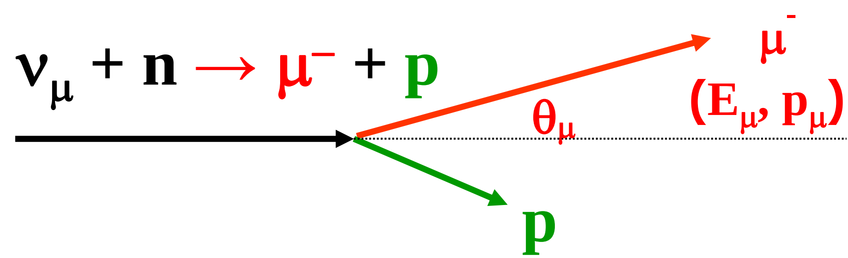
Fin.

Introduction

Case 1: $E\nu$ = 100MeV ~ a few GeV

$\nu + N \rightarrow l + N'$ Charged current quasi-elastic scattering events





Accelerator based experiment -> Direction of neutrino is known

Use direction and momentum of lepton
to reconstruct energy of neutrino

- Purity of the selected events
- Binding effects of target nucleus
  Fermi momentum, Binding energy etc.
- Contamination ~ Impurity
  Interactions other than genuine CCQE
- Multi-nucleon interaction?

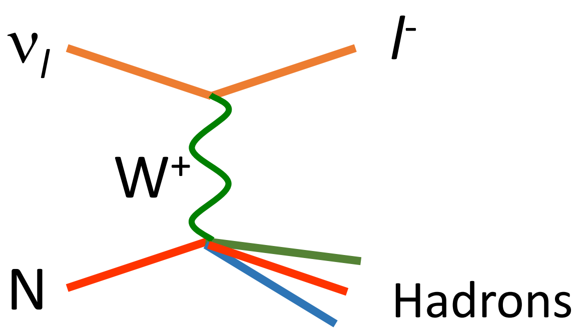
Introduction

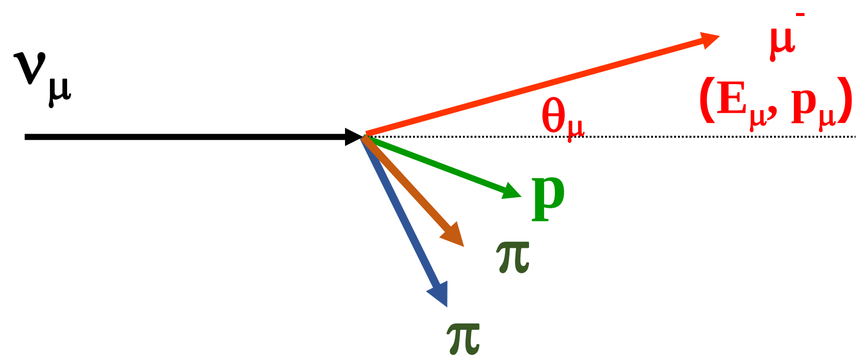
Case 2: Eν > several GeV

Charged current interactions,

mainly **ν + N → *l* + N' + hadrons**

(Charged current deep inelastic scattering evens)





Use direction and momentum of lepton together with the observed energy of hadrons to estimate the energy of neutrino.

Event topologies of neutral current interactions and (anti neutrino) electron neutrino charged current interactions are quite similar in some detectors.