Studies on lepton-hadron interactions for precision neutrino physics

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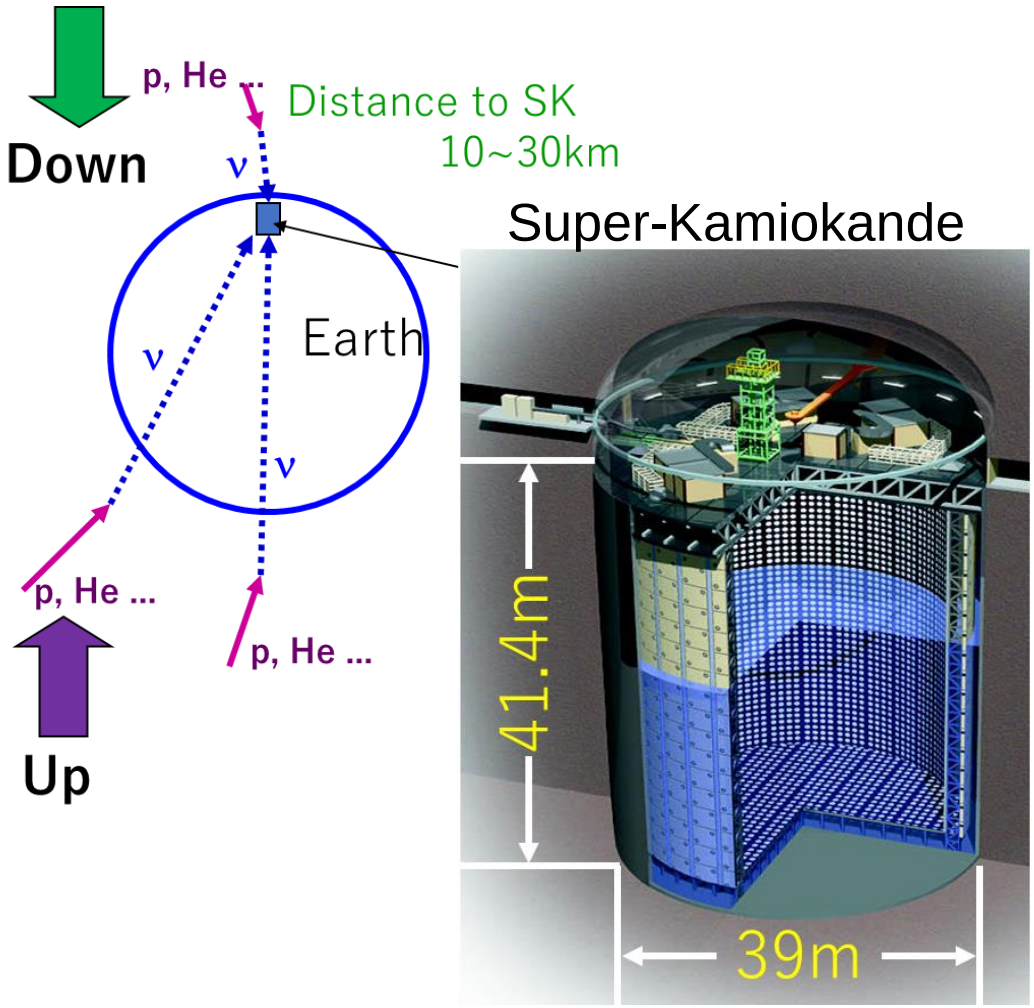
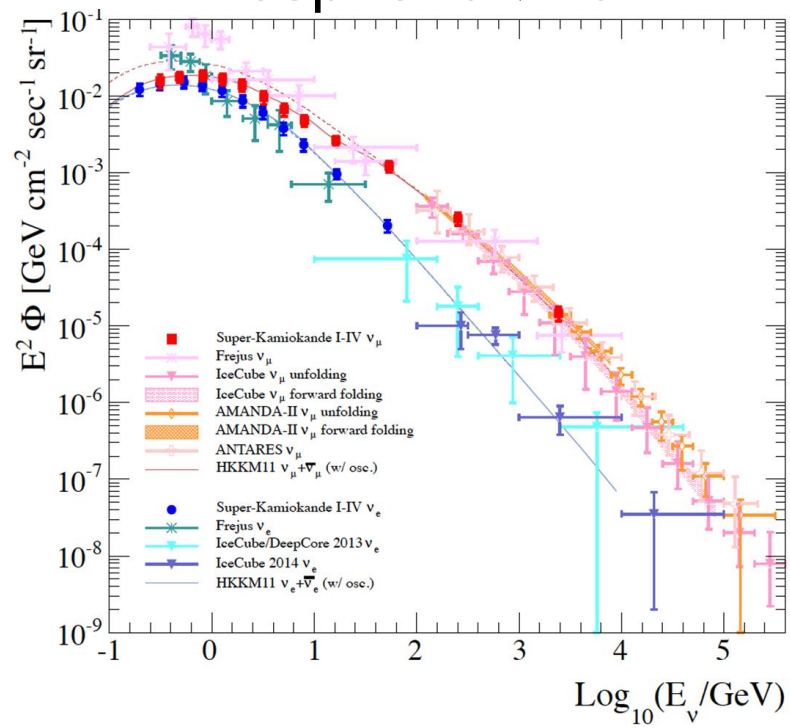
Discovery of neutrino oscillation

1996 Neutrino oscillation was discovered at Super-Kamiokande



Atmospheric ν flux

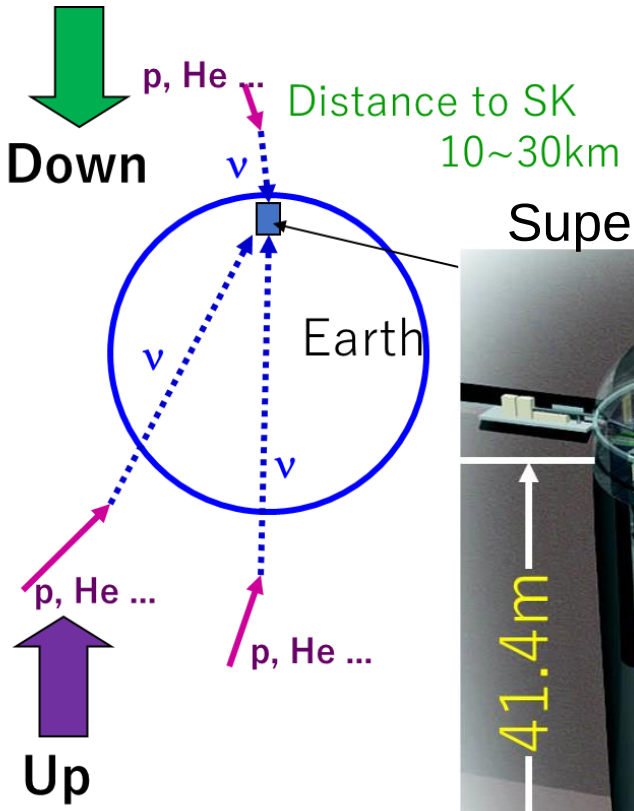


peak at a few hundreds of MeV
up to > 100 TeV

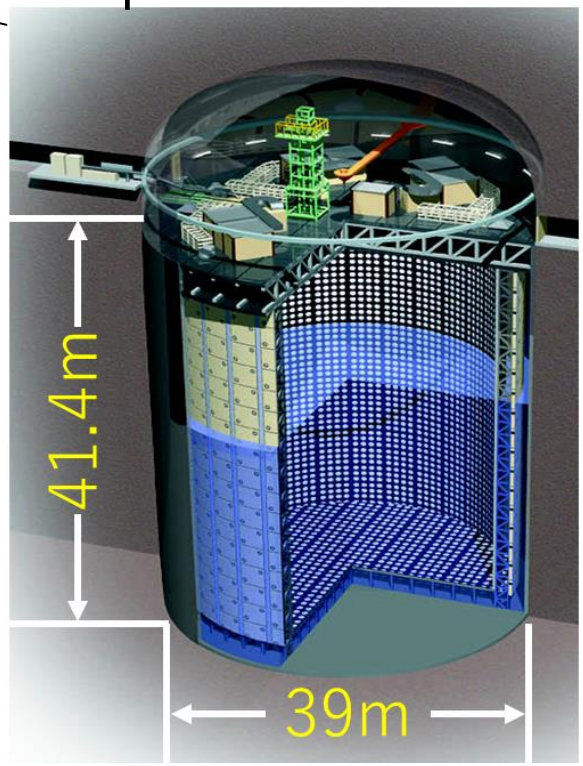
Discovery of neutrino oscillation

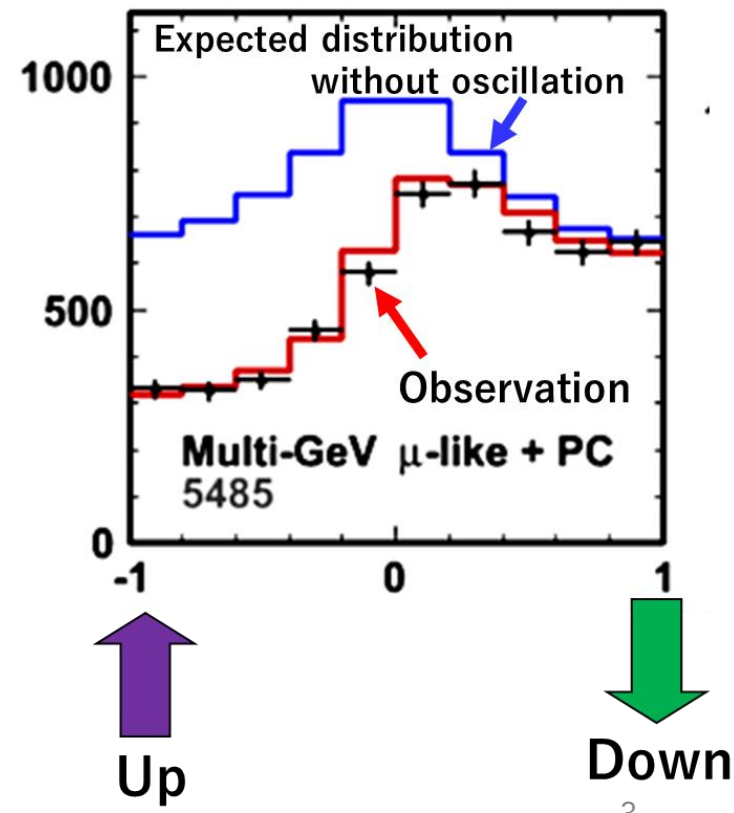
1996 Neutrino oscillation was discovered at Super-Kamiokande

Clear up/down asymmetry observed
~ Deficit of upward going ν_μ



Super-Kamiokande





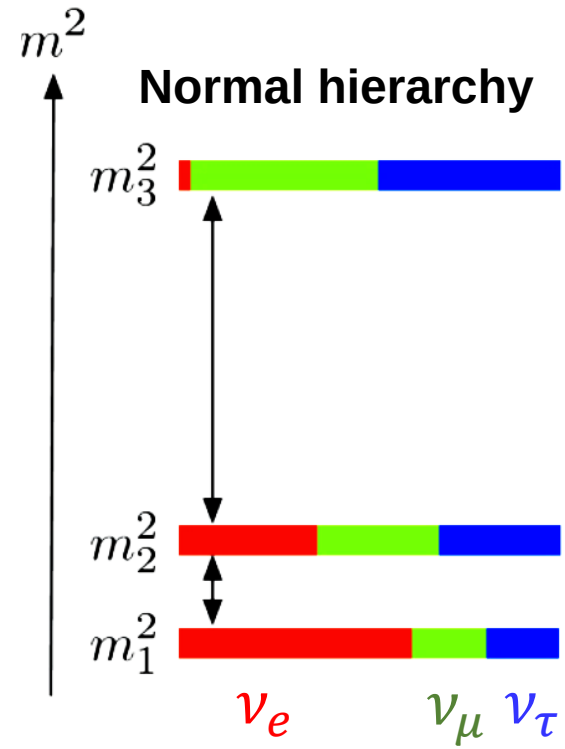
Neutrino oscillation and properties of neutrinos

Neutrino oscillations

- Non-zero neutrino mass states $(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3)$
- Flavor mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$
2 mass differences $(\Delta\mathrm{m}^2_{32}, \Delta\mathrm{m}^2_{21})$
1 CP phase (δ_{CP})



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \cdot \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \cdot \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

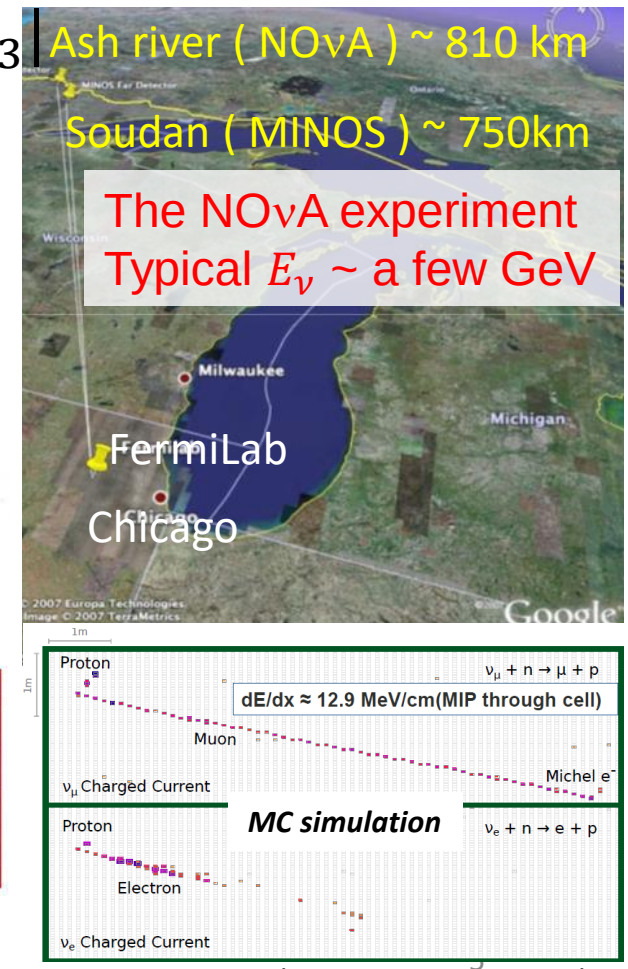
$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Accelerator based long baseline neutrino oscillation experiments

Produce ν_μ / $\overline{\nu_\mu}$ beam using high intensity proton source.
Baselines are a few hundreds to thousand km.
Study ν_μ disappearance. → θ_{23} and $|\Delta m^2_{23}|$
Study ν_e appearance.
→ θ_{13}, CP violation and mass hierarchy.

The T2K experiment

Typical E_ν ~ 600MeV



L. Suter(FNAL User meeting)

Determination of properties of neutrinos

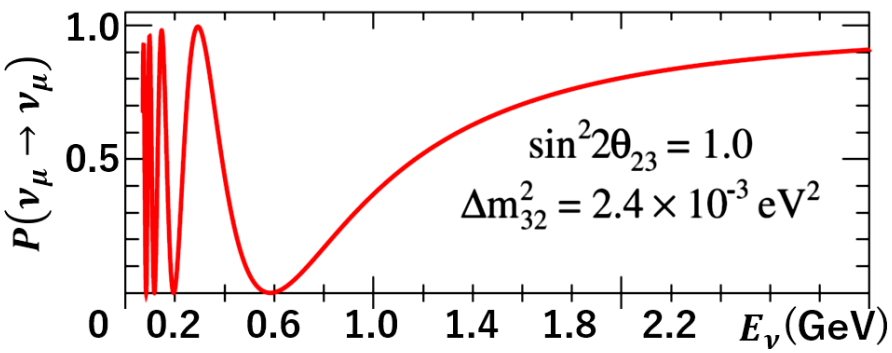
Neutrino oscillation probability (survival probability)

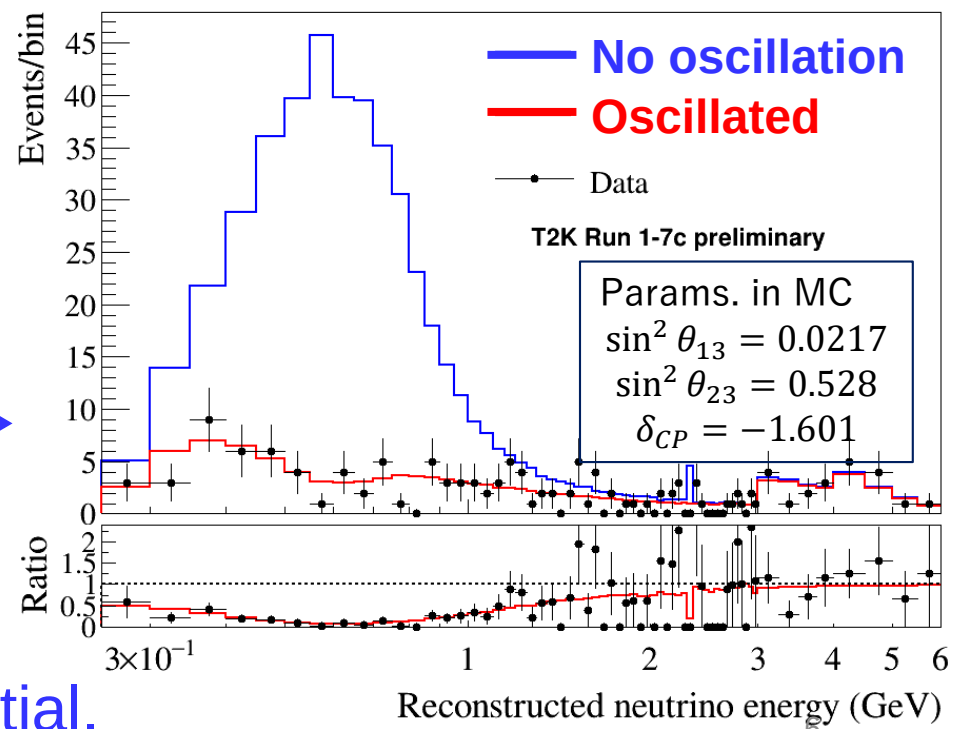
2 Flavor case (simplified)

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

θ Mixing angle, Δm^2 Squared mass difference (in eV^2)

L Distance (in km), E_ν Energy of neutrino (in GeV)





Neutrino energy spectrum distortion.

Correct "estimation" of neutrino energy is essential.

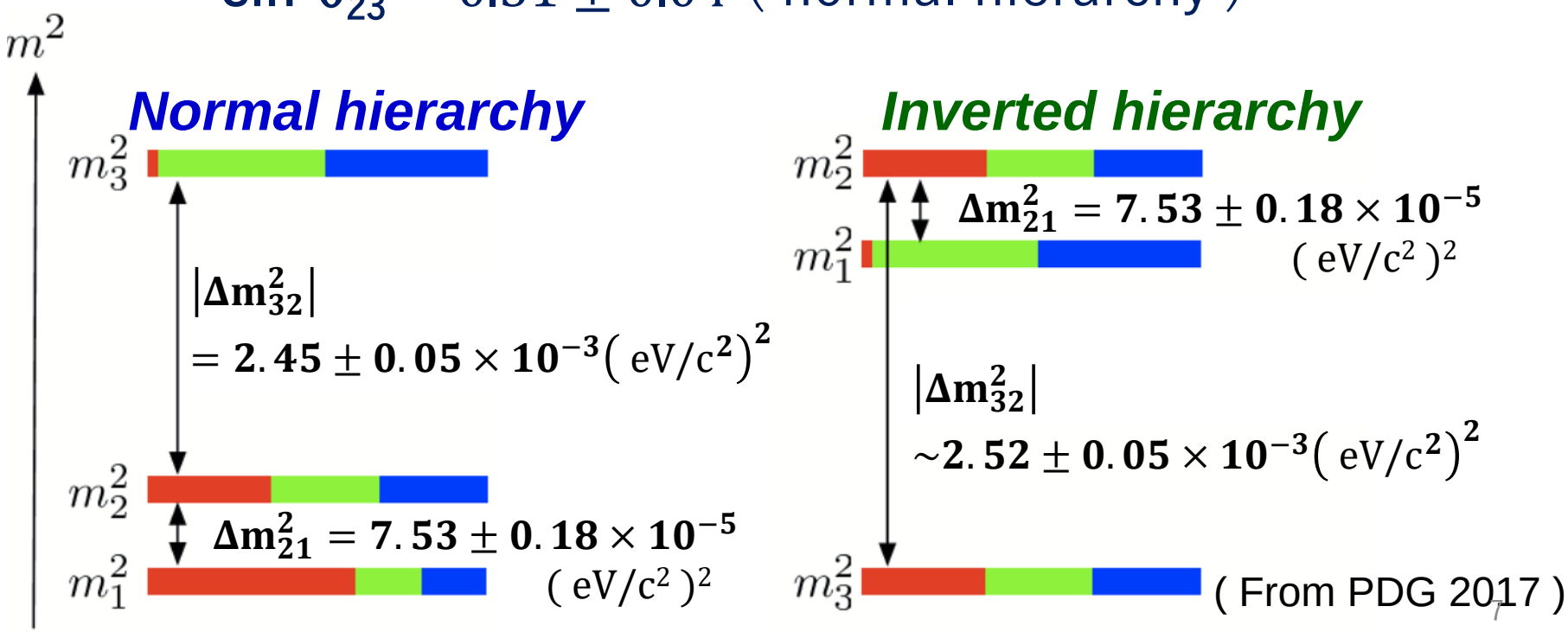
Properties of neutrinos

All angles except for $\boldsymbol{\delta_{CP}}$ have been measured.

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \cdot \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \cdot \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2\theta_{12} = 0.307 \pm 0.013$ $\sin^2\theta_{13} = 0.0210 \pm 0.0011$

$\sin^2\theta_{23} = 0.51 \pm 0.04$ (normal hierarchy)



(From PDG 2017)

Properties of neutrinos ~ **Remaining questions**

1) Is θ_{23} really 45° or < 45° or >45° ?

$\sin^2\theta_{23}$ = 0.51 ± 0.04 (normal hierarchy)

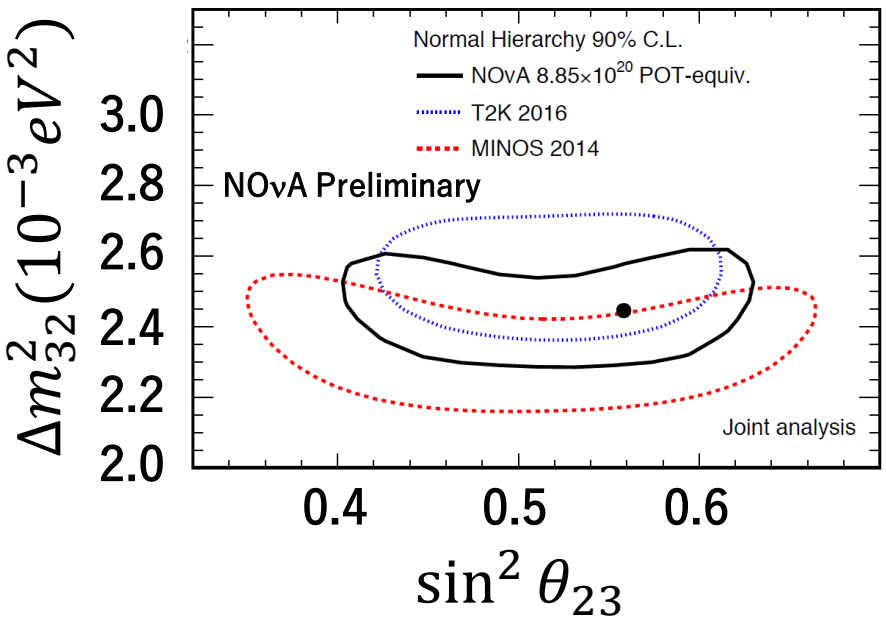
→ Precise measurement of ν_μ disappearance

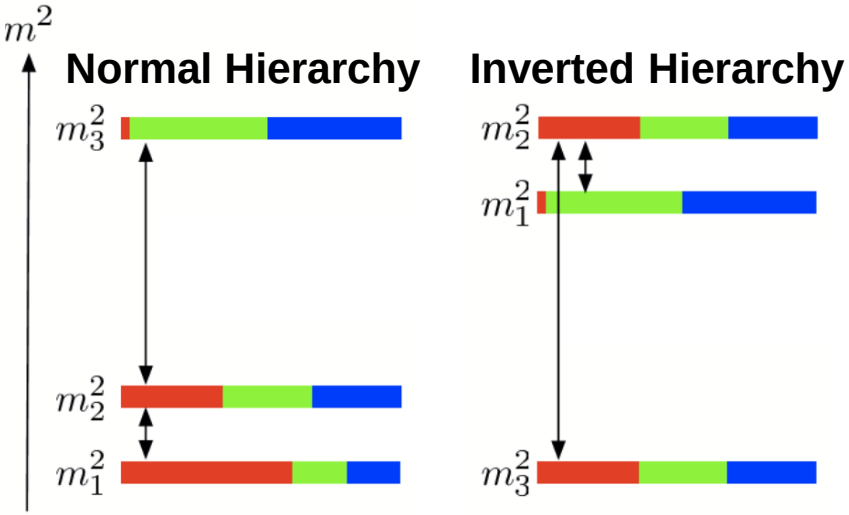
2) Mass hierarchy ~ which is heavier ?

$\Delta m^2_{32} > 0$ or < 0 ?

3) Is CP violated (δ_{CP} = 0 or not) ?

→ Study difference between $\nu_\mu \to \nu_e$ and $\overline{\nu_\mu} \to \overline{\nu_e}$





Determination of neutrino oscillation parameters

Neutrino oscillation probability ~ Appearance (3 flavor)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$$

θ_{13} leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\cdot\sin\Phi_{31}\cdot\sin\Phi_{21}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32}\cdot\sin\Phi_{31}\cdot\sin\Phi_{21}$$

CP odd term

$$+4S_{12}^2 C_{13}^2 \left(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right)\sin^2\Phi_{21}$$

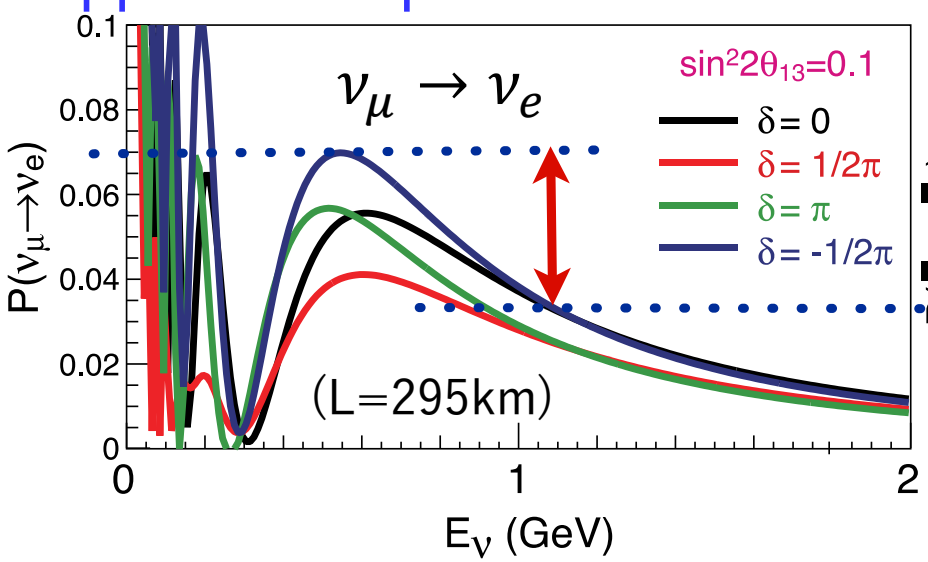
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \left(1 - 2S_{13}^2\right)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31}.$$

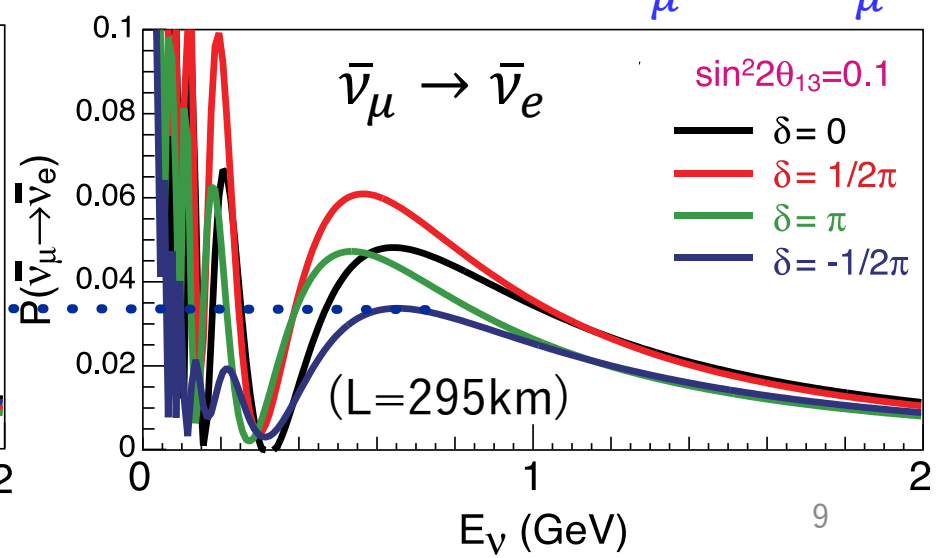
Matter term

$$a = 2\sqrt{2}G_F n_e E_\nu \quad c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}, \Phi_{ij} = \frac{1.27\Delta m_{ij}^2 L}{E_\nu}$$

For anti neutrinos, $a \to -a, \delta \to -\delta$

Appearance probabilities could be different between ν_μ and $\overline{\nu_\mu}$.





Determination of neutrino oscillation parameters

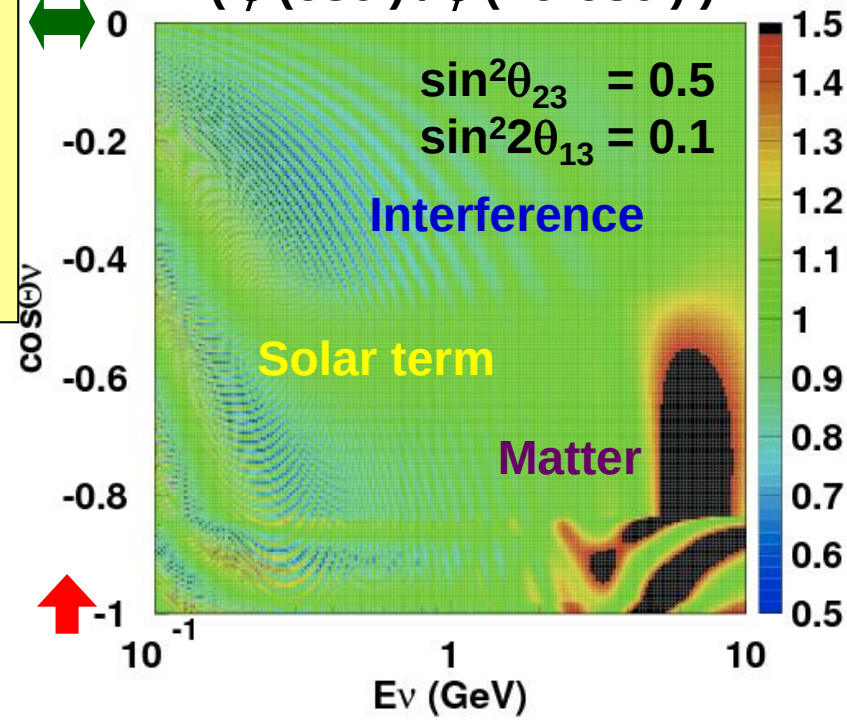
Determination of mass hierarchy
using matter effects in atmospheric neutrino oscillation

Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m_{12}^2) + \Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$$

- $\Delta_1(\theta_{13})$ ← **Matter effect**
- $\Delta_2(\Delta m_{12}^2)$ ← **Solar term**
- $\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$ ← **Interference**

ν_e flux ratio
(ϕ (osc.) / ϕ (no-osc.))



Normal and inverted hierarchies give different ν_e and $\bar{\nu}_e$ appearance probabilities in a few GeV region of atmospheric neutrinos.

Neutrino / anti-neutrino separation is performed by event topology, # of neutrons. etc.

It is also possible to determine mass hierarchy using neutrinos from accelerators.

Neutrino-nucleon/nucleus interactions above 100 MeV

Charged current quasi-elastic scattering (CCQE)

$$\nu + N \rightarrow l^- + N'$$

Neutral current elastic scattering

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

Single meson productions

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

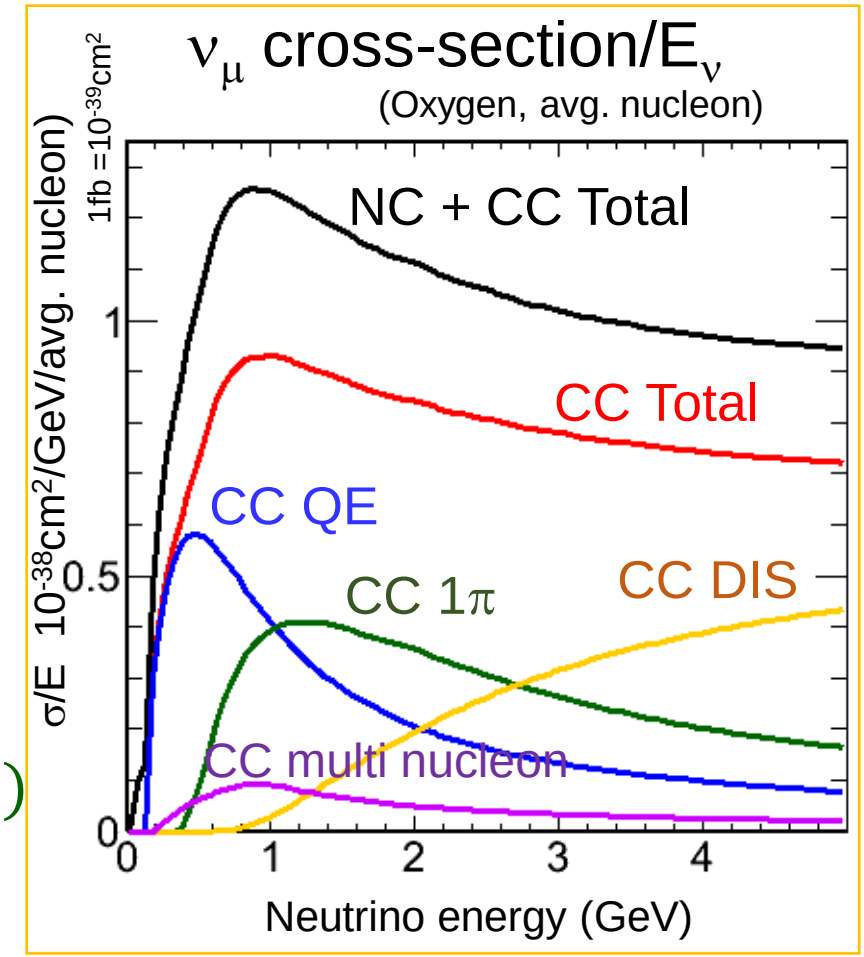
Single photon productions

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

(radiative decay of resonance)

Deep inelastic scattering

$$\nu + N \rightarrow l^- + N' + n \times \pi\ (\eta, K\ )$$



Neutrino detectors ~ nucleus target

Various “nuclear effects” have to be taken into account.

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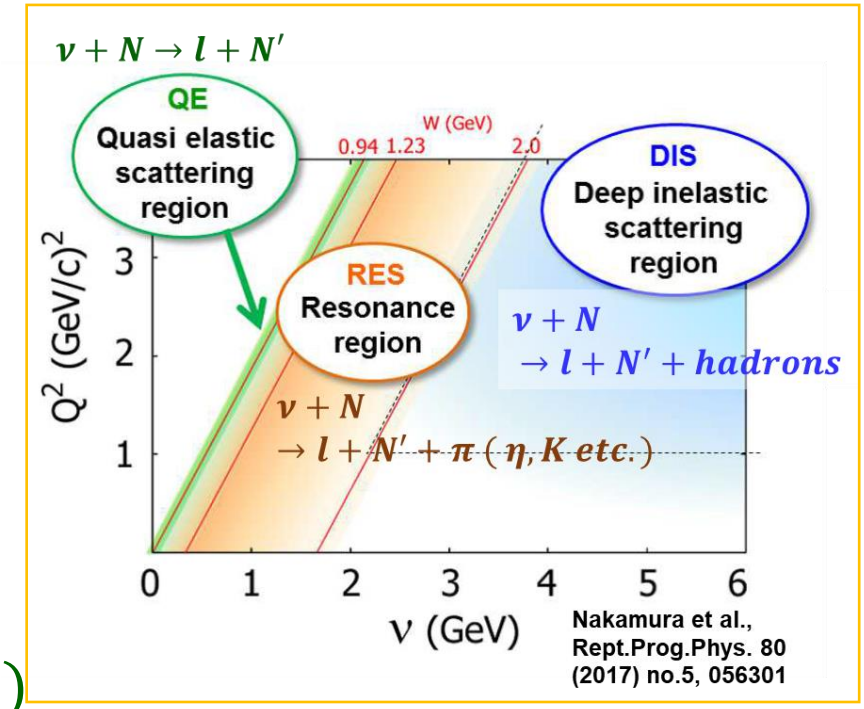


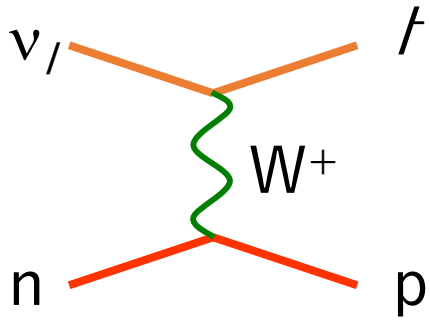
Neutrino detectors ~ nucleus target

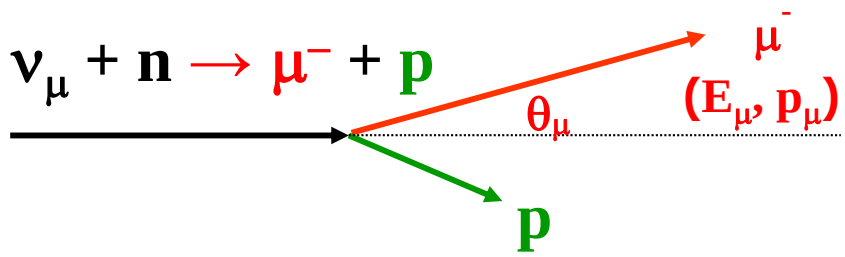
Various “nuclear effects” have to be taken into account.

Methodology of neutrino oscillation experiments

Case 1: E_ν = 100MeV ~ a few GeV

ν + N → *l* + N' Charged current quasi-elastic scattering





Accelerator based experiment → Known neutrino direction

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?

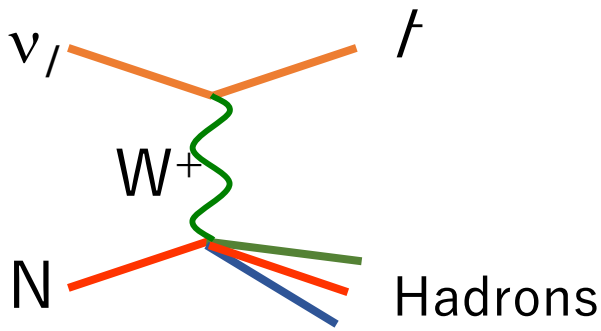
Methodology of neutrino oscillation experiments

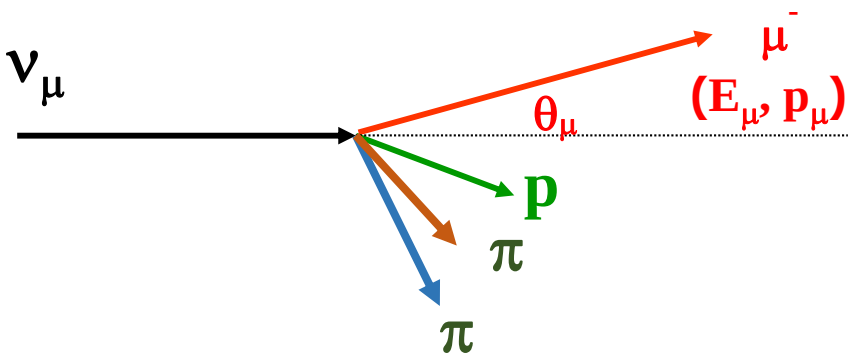
Case 2: E_ν > several GeV

Charged current interactions,

mainly **ν + N → *l* + N' + hadrons**

(Charged current deep/shallow inelastic scattering)





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 electron neutrino charged current interactions

are quite similar in some detectors.

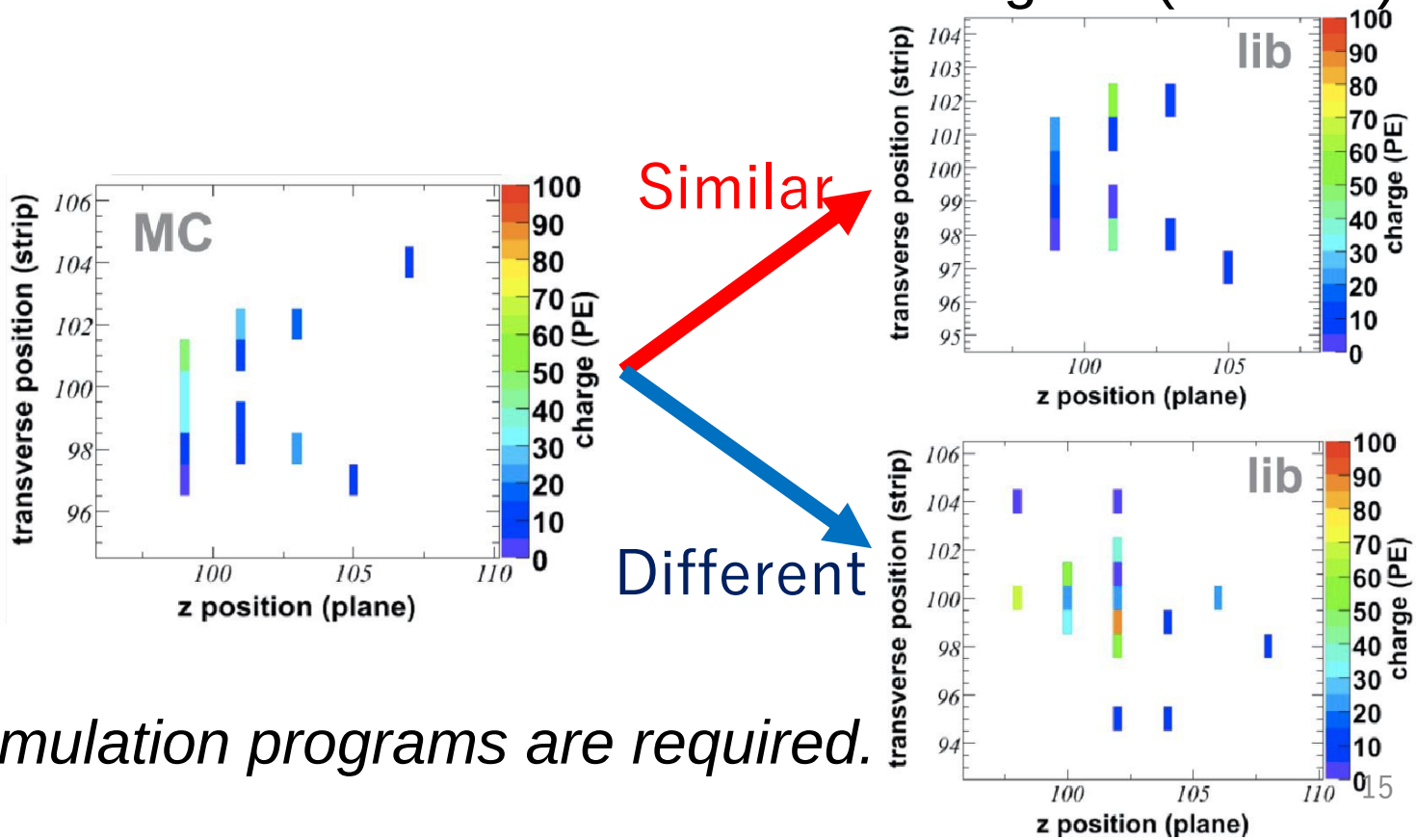
Methodology of neutrino oscillation experiments

Case 2: E_ν > several GeV

Charged current interactions,

mainly **ν + N → *l* + N' + hadrons**

Neutrino interaction / flavor identification using simulated data catalogues (MINOS)



Precise simulation programs are required.

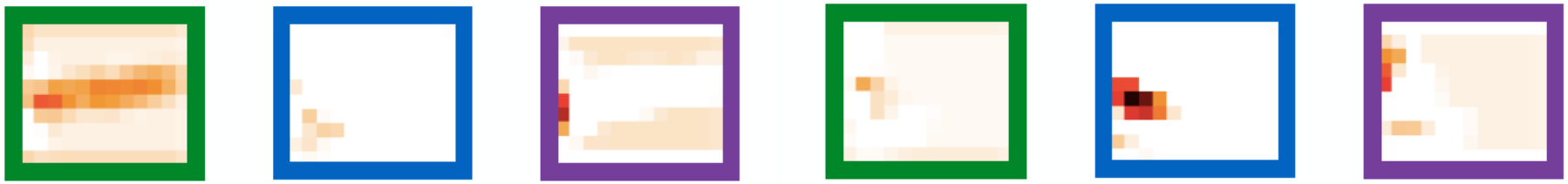
Methodology of neutrino oscillation experiments

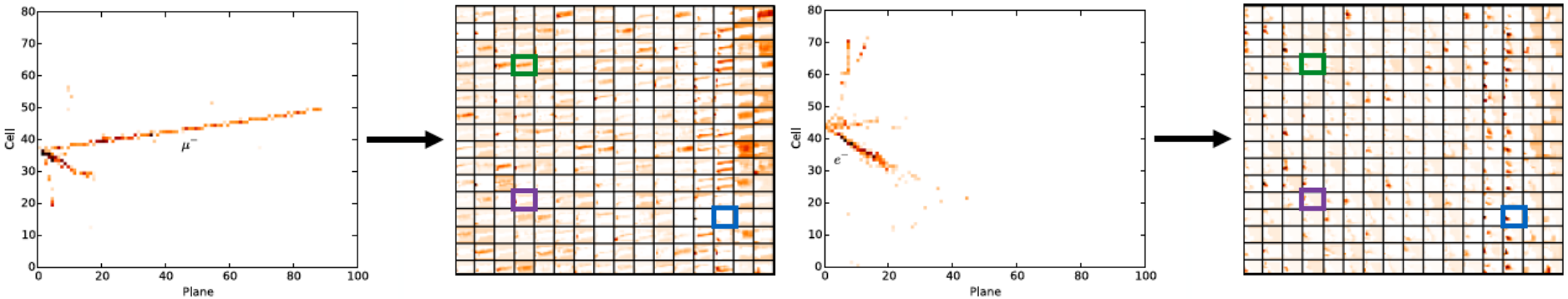
Case 2: E_ν > several GeV

Charged current interactions,

mainly **ν + N → *l* + N' + hadrons**

Neutrino flavor identification using neural network (NOνA)





A. Aurisano et al., arXiv:1604.01444

Improvement in sensitivity from CVN equivalent to 30% more exposure

Precise simulation programs are required.

Determination of neutrino oscillation parameters

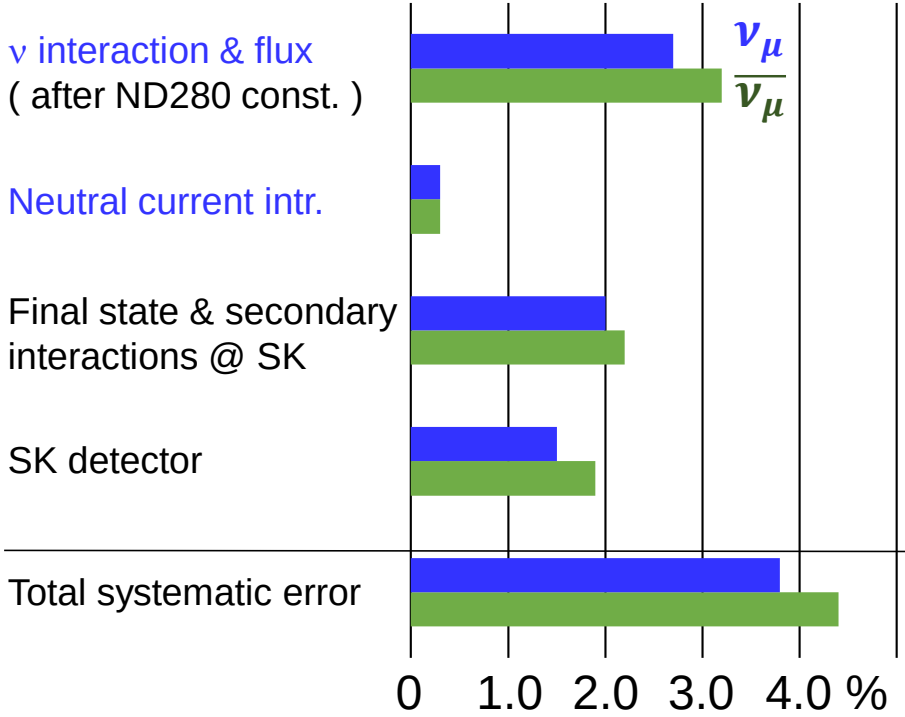
Neutrino-nucleus interactions

~ Major source of uncertainties in oscillation analyses

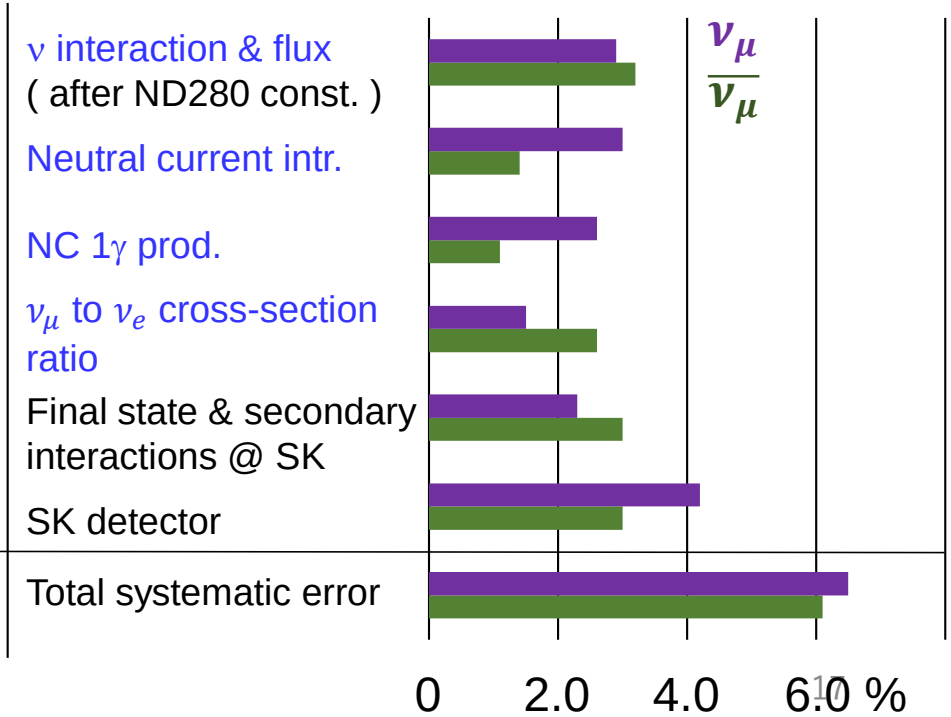
Dedicated neutrino detectors are located in the ν beamline to measure ν flux and interactions.

Systematic error for # of events (for 1 ring events) @ T2K

ν_μ / $\overline{\nu_\mu}$ 1 ring μ-like sample



ν_μ / $\overline{\nu_\mu}$ 1 ring e-like samples

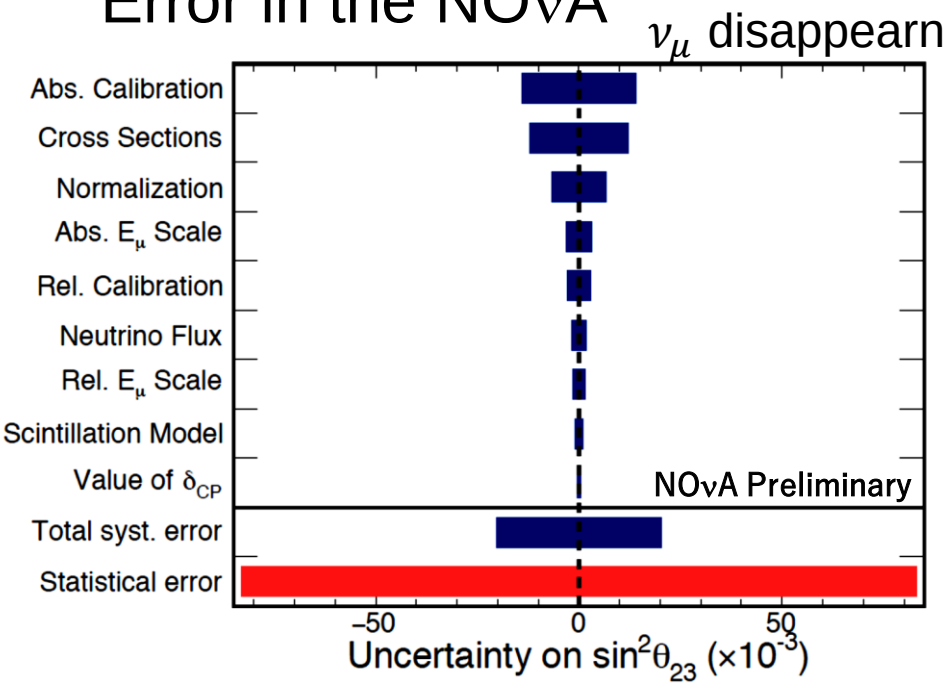


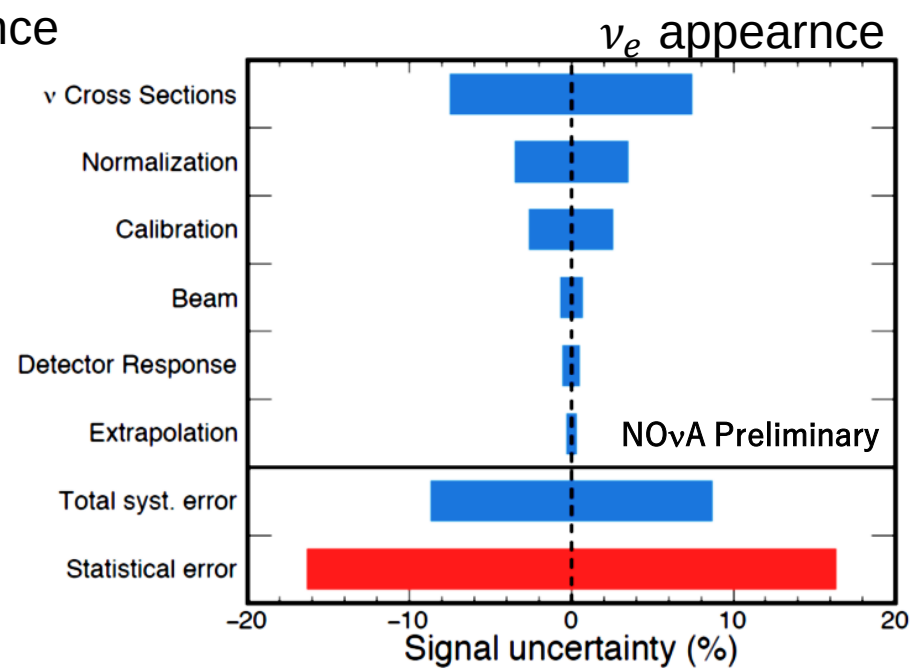
Determination of neutrino oscillation parameters

Neutrino-nucleus interactions

~ Major source of uncertainties in oscillation analyses

Error in the NOνA





Need to understand the neutrino-nucleus interaction.
This will reduce the errors from neutrino-nucleus interactions and also, improve the accuracy of the flux measurements with the near detectors.

Accelerator based neutrino oscillation experiments

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

These experiments use "nuclear" targets.

CH (Scintillator) T2K ND, NOνA

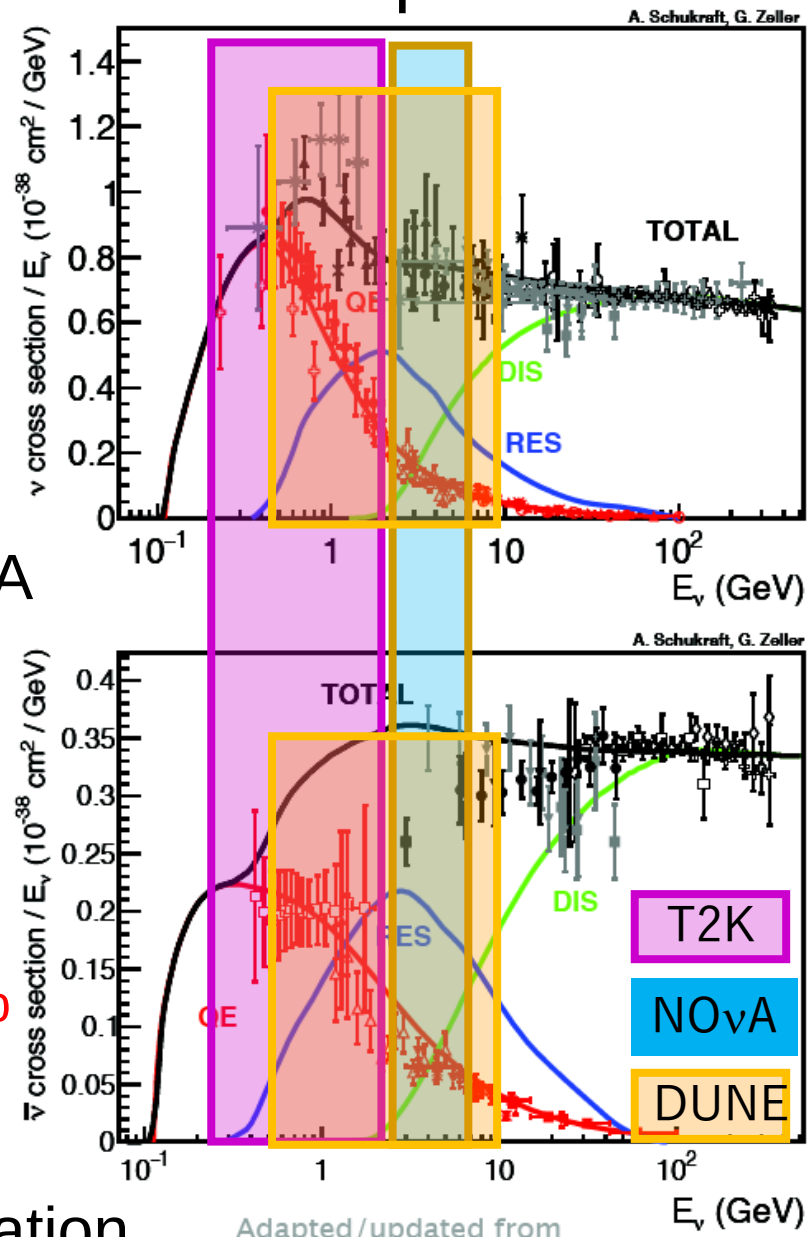
H_2O (Water) Super-K, T2K FD and Hyper-K

Ar. (Lq. Ar TPC) DUNE

Systematic uncertainty is required to be less than a few % to achieve physics goals like

CP violation study

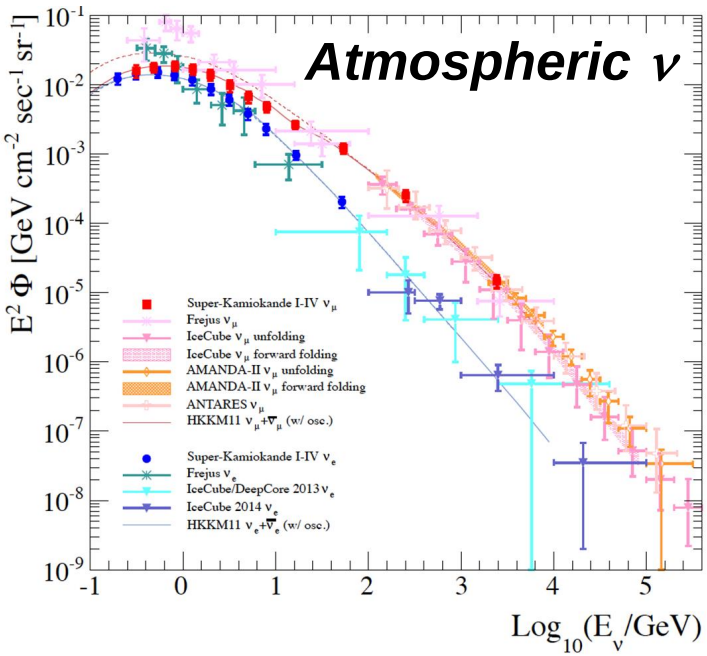
Mass hierarchy determination.

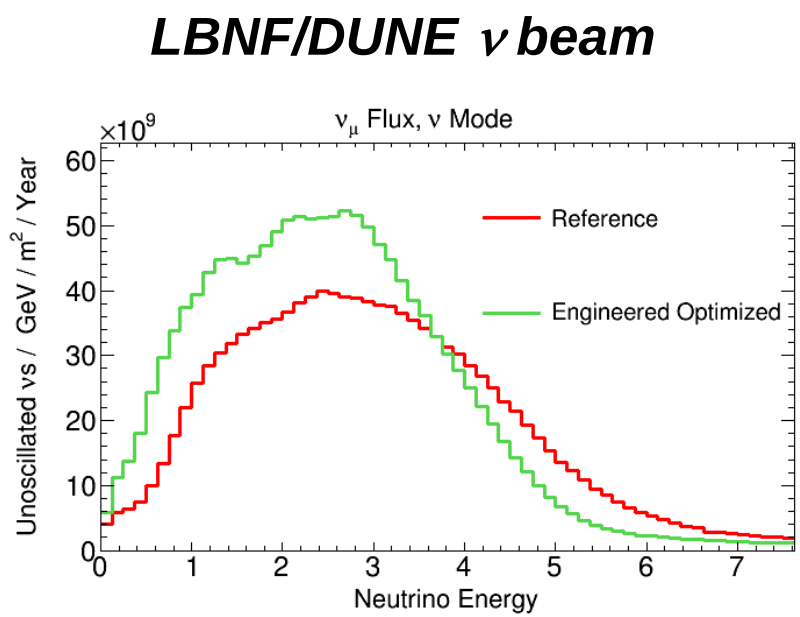


Adapted/updated from J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Difficulties in the neutrino oscillation experiments

1) Neutrino beam energy is not monochromatic





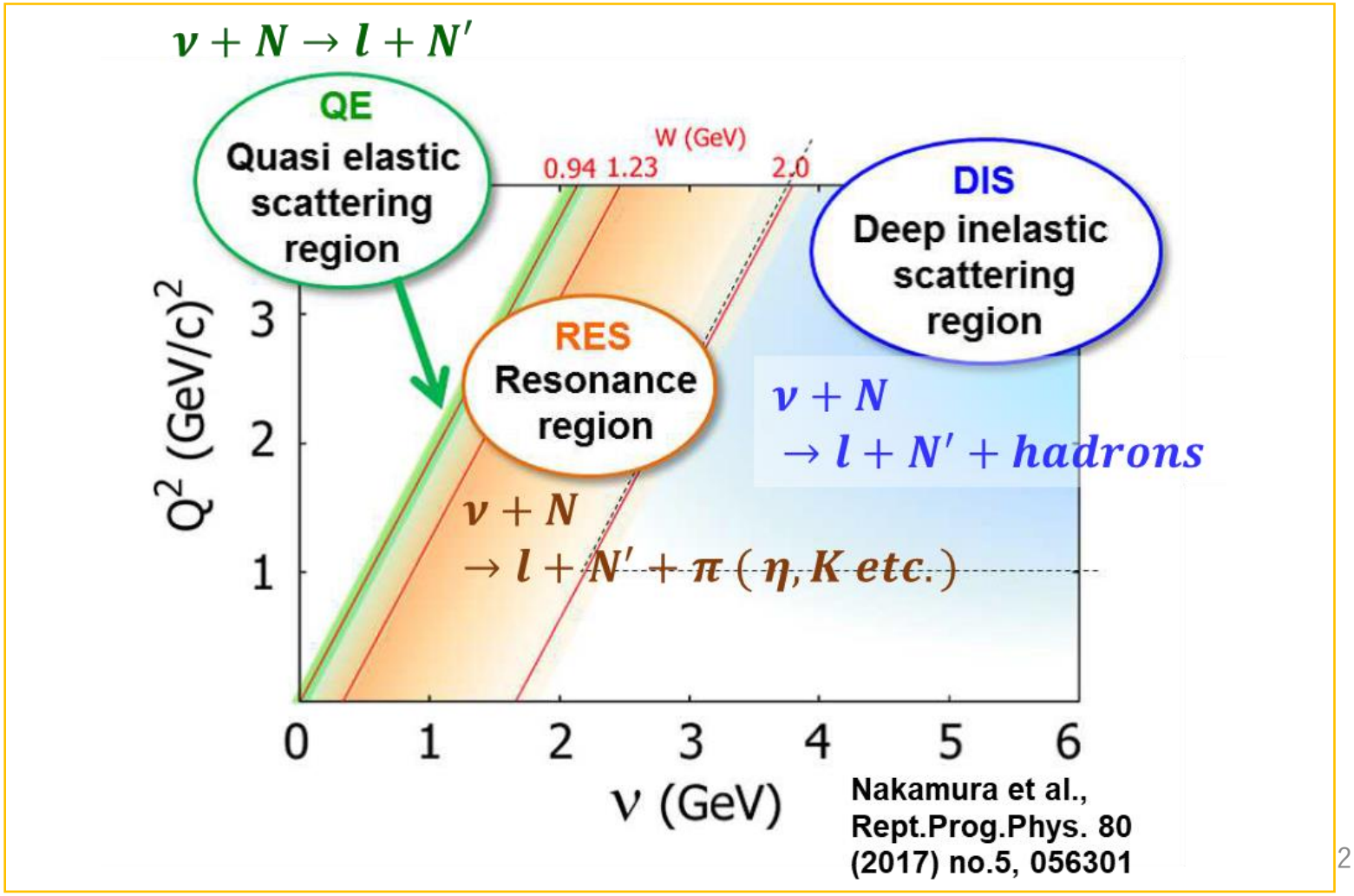
Energy of each observed "neutrino" is reconstructed from experimental observables

or

observables (distributions) are compared with the simulation using the "oscillated" neutrino flux.

Difficulties in the neutrino oscillation experiments

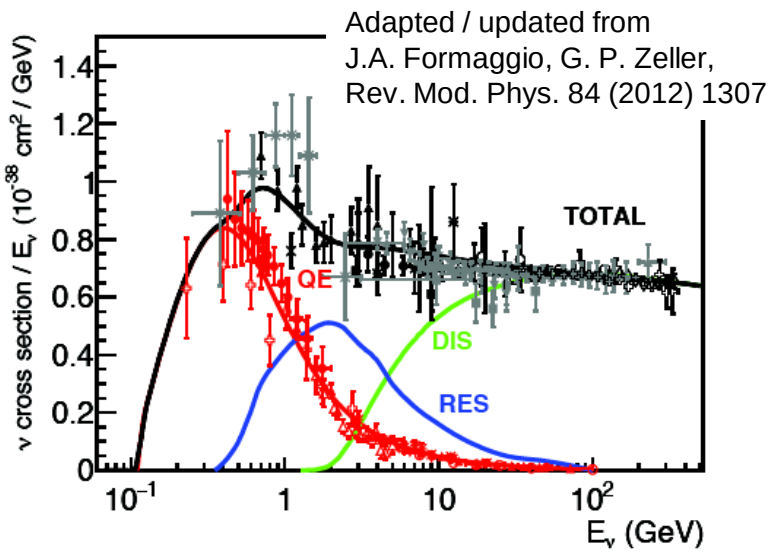
2) Various kinds of interactions are contained in the sample. Exact energy transfer or momentum transfer values are not available.

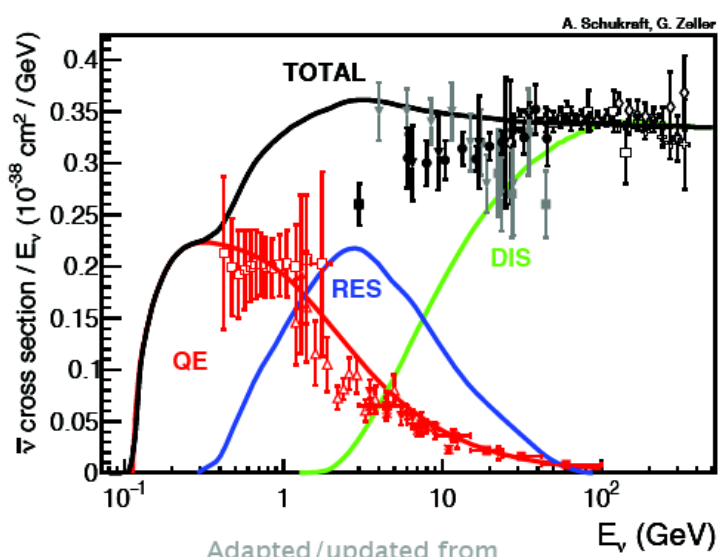


Difficulties in the neutrino oscillation experiments

3) Understanding of neutrino-nucleus interactions are far from perfect.

- Neutrino-nucleon scattering data
  D_2 Bubble chamber data in ’70s ~ ’80s
  Low statistics and large systematic errors.
- Recently, there are high quality neutrino-nucleus scattering data are available.
  However, acceptances of low momentum nucleons are insufficient.





Deep inelastic scatterings

$\nu + N \rightarrow l + \text{hadrons}$

Dominant interaction in the high energy region

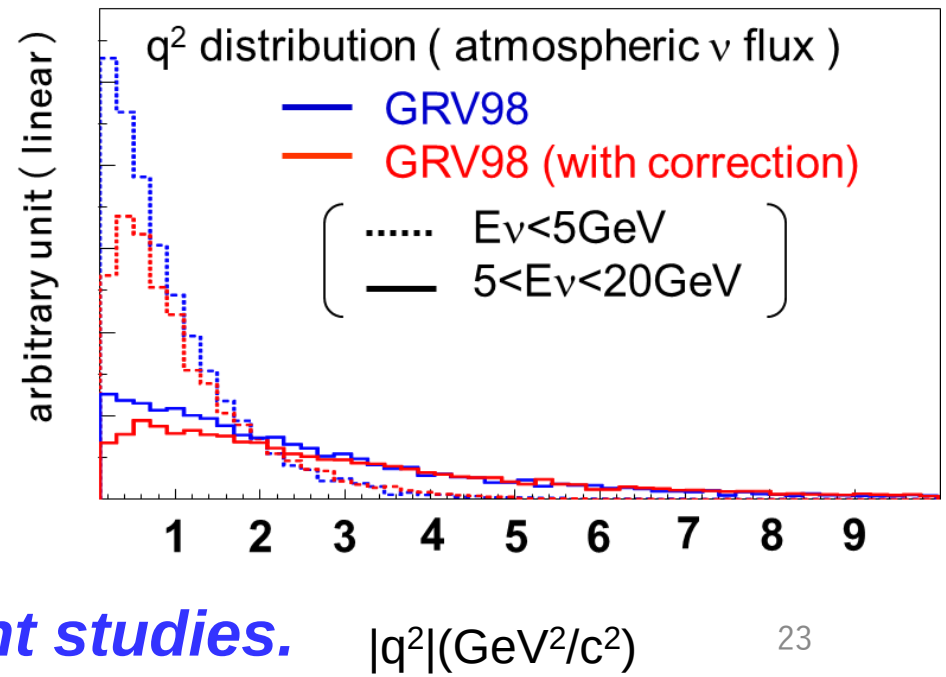
$$\frac{d^2\sigma^\nu}{dxdy} = \frac{G_F^2 m_N E_\nu}{\pi}\left[(1-y+\frac{1}{2}y^2+C_1)F_2(x)+y(1-\frac{1}{2}y+C_2)[xF_3(x)]\right]$$

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

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

However, PDFs are not valid for small $|q^2|$ and small W.

Bodek & Yang proposed low q^2 corrections for GRV98. (Fit various data to extract correction factors.)



Experiments use their correction in the simulation.

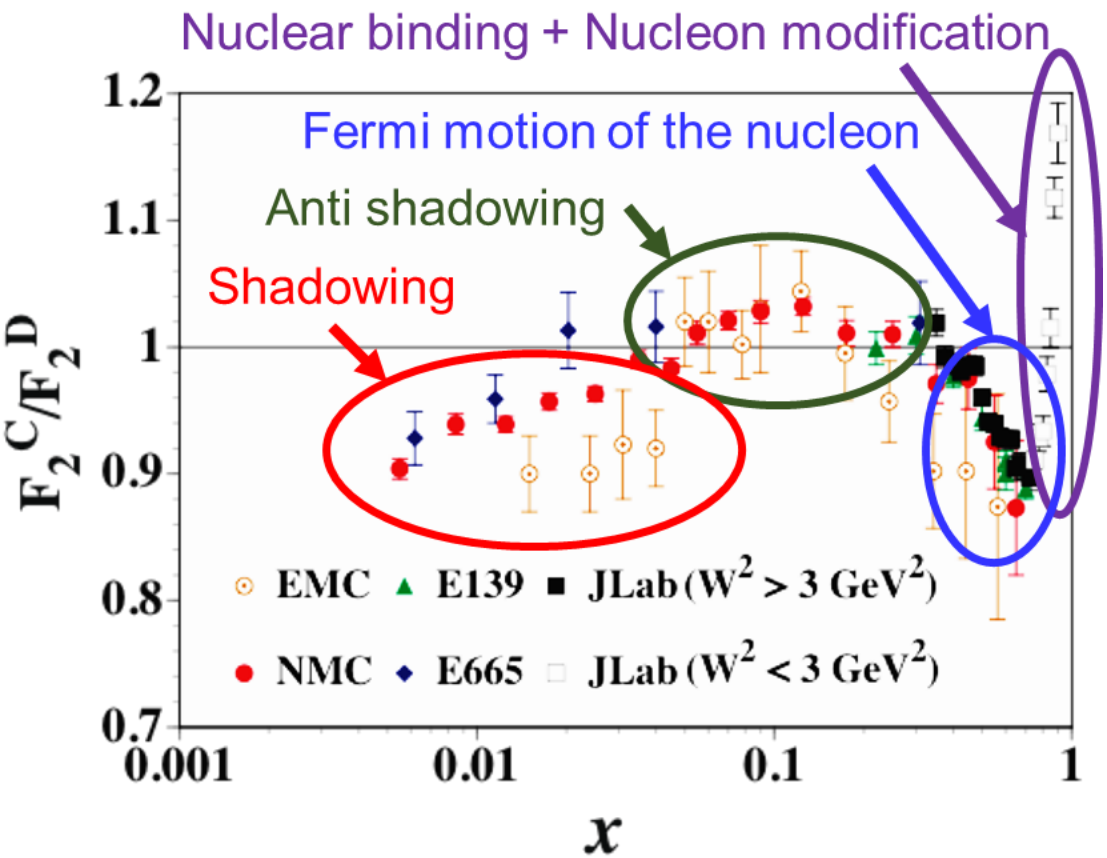
Better to have independent studies.

Deep inelastic scatterings

$\nu + N \rightarrow l + \text{hadrons}$

Structure function is known to have nuclear modifications

Known to exist nuclear modification of structure function F_2.



D.F. Geesman, K. Saito, A.W. Thomas,
Ann. Rev. Nucl. Part. Sci. 45 (1995) 337 & S. Kumano (NuINT17)

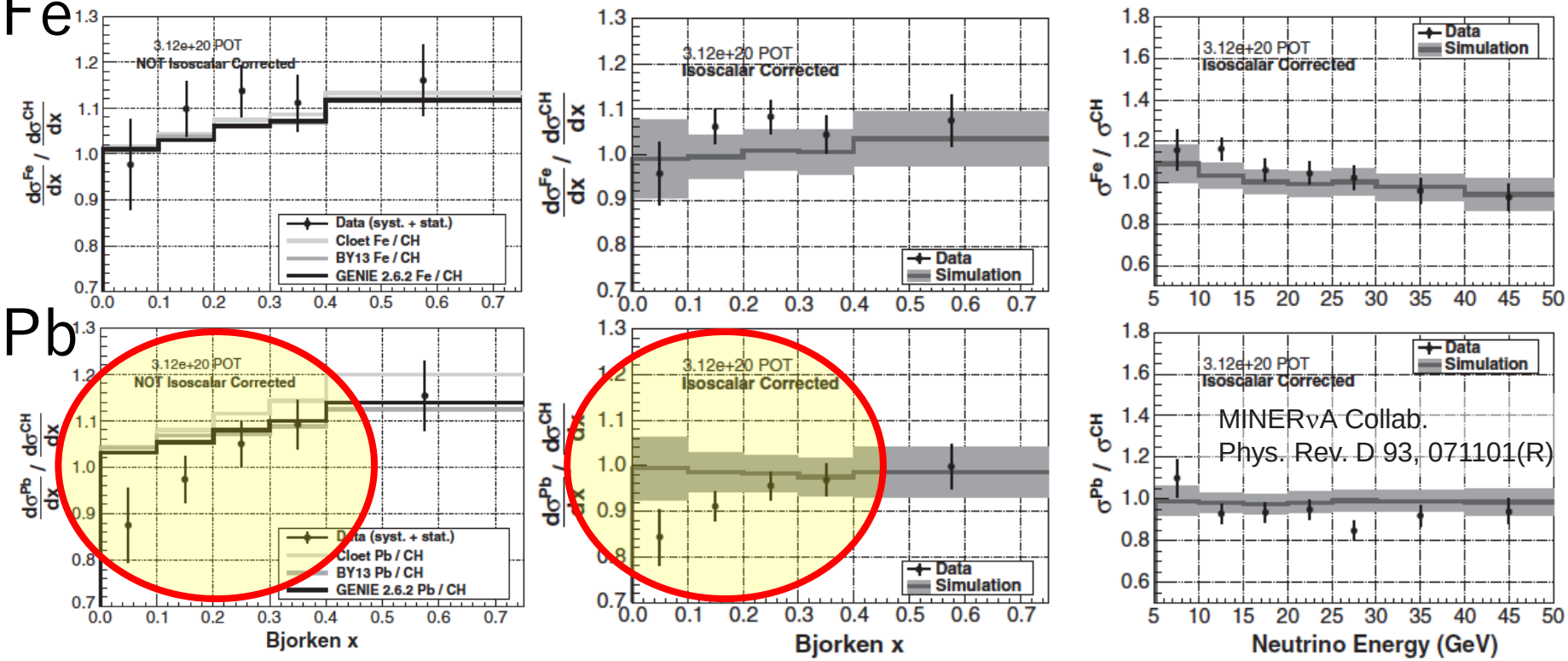
How about xF_3?

Deep inelastic scatterings

$\nu + N \rightarrow l + \text{hadrons}$

Structure function is known to have nuclear modifications

Recently, nuclear dependences of
neutrino-nucleus differential cross-section was reported
but the behavior seems to be different from electron scattering.

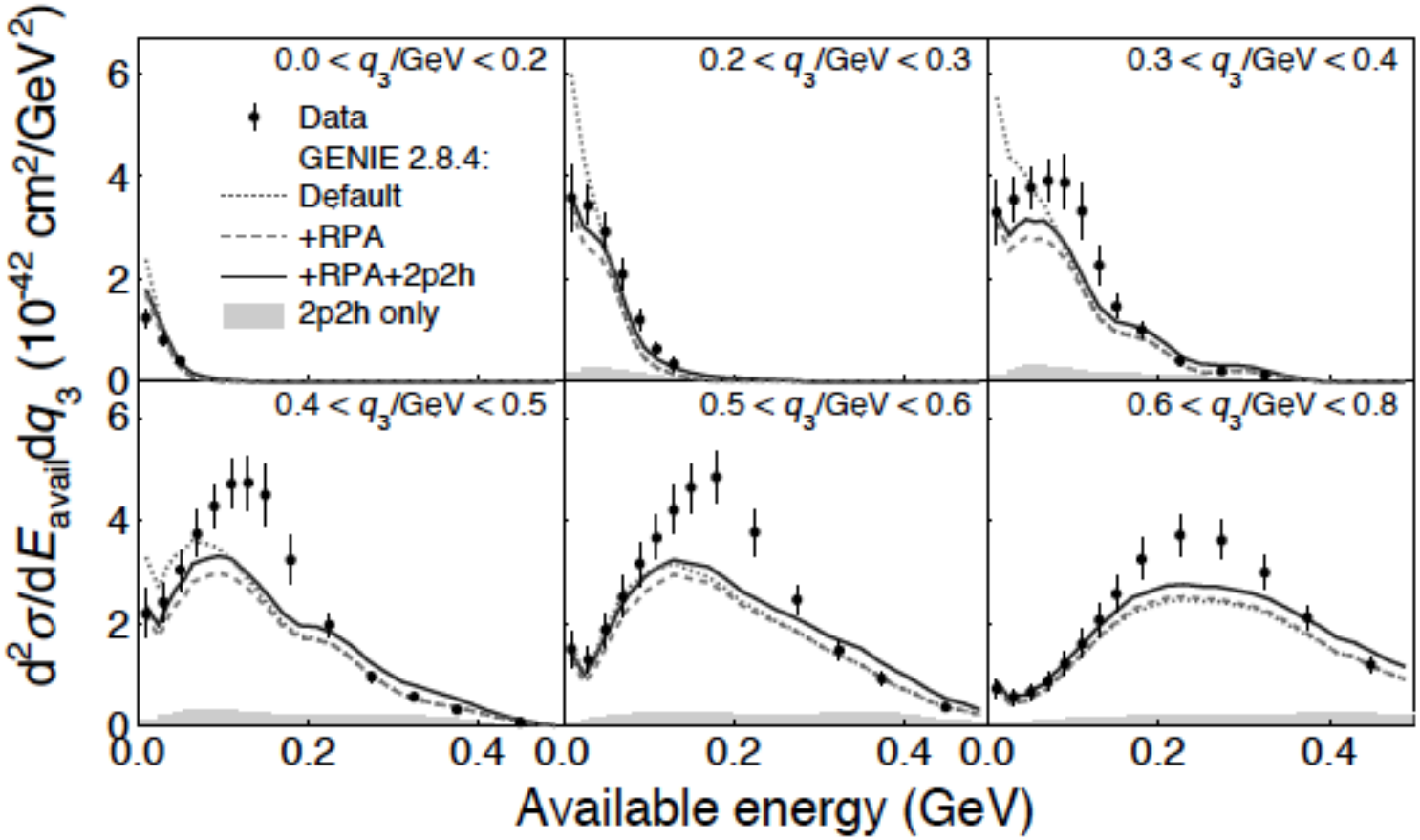


Theoretical studies of "nuclear PDF" have been started.

Further measurements and studies are necessary.

Inclusive neutrino-nucleus scattering measurements

MINERνA experiment measured the relation
between reconstructed 3 momentum transfer
and observed energy of hadrons.
However, their simulation program can not reproduce the distribution.



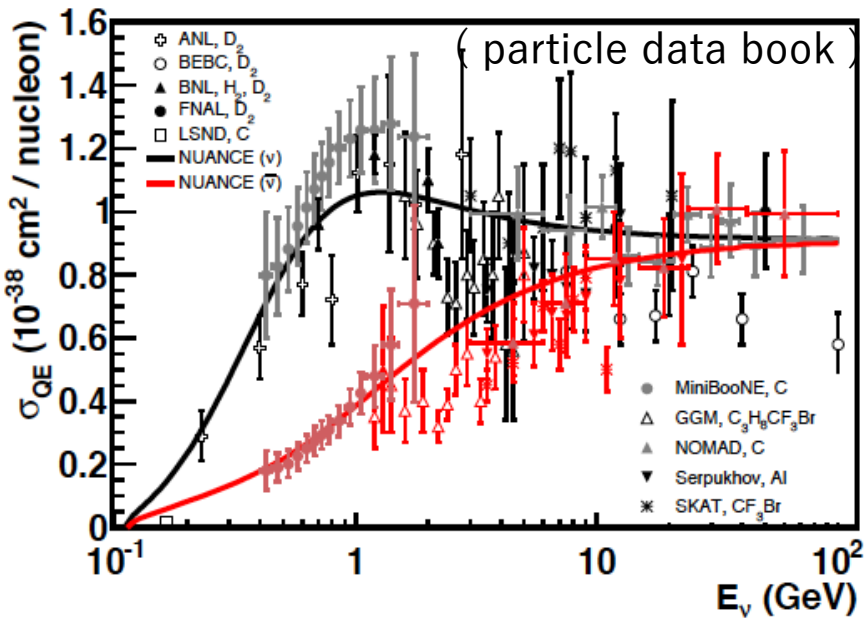
Due to multi-nucleon interactions $(\nu + N_1 + N_2 \rightarrow l^- + N_1' + N_2'')$ **?**

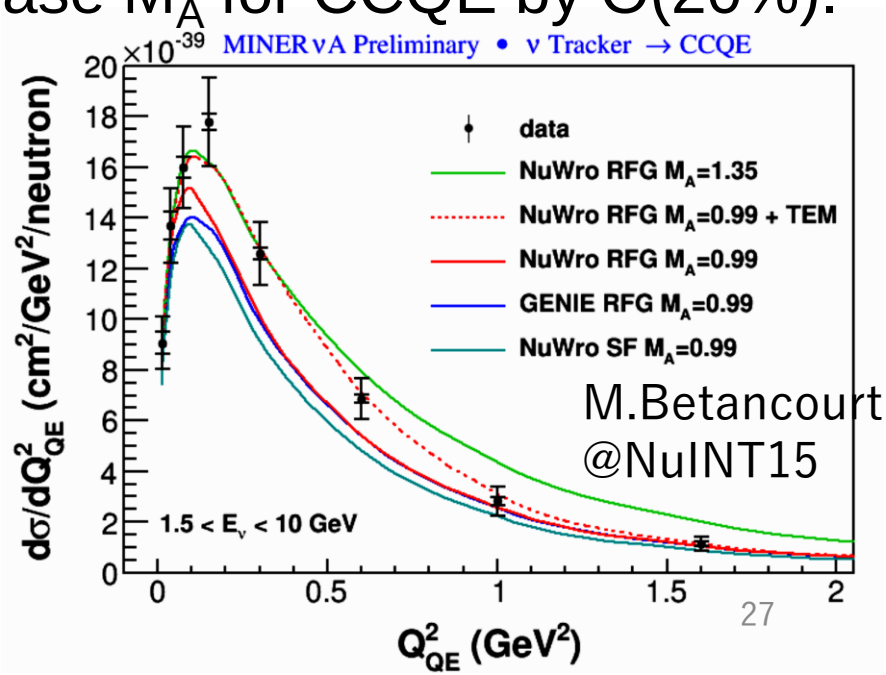
Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

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%).

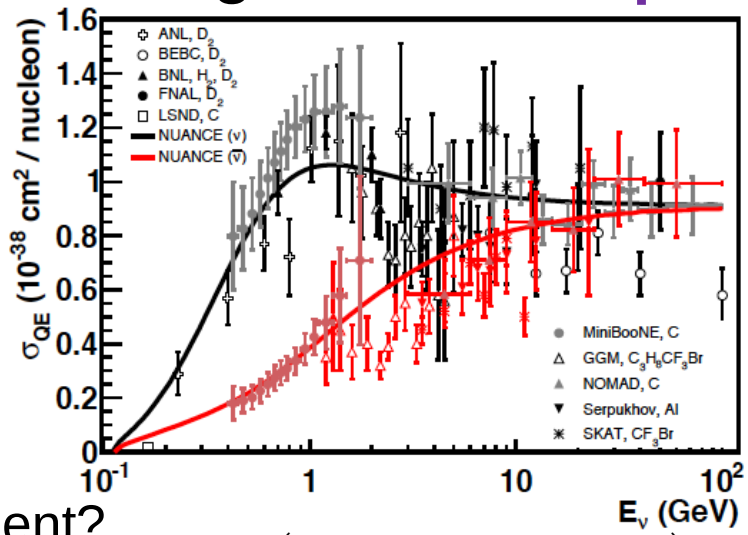




M.Betancourt
@NuINT15

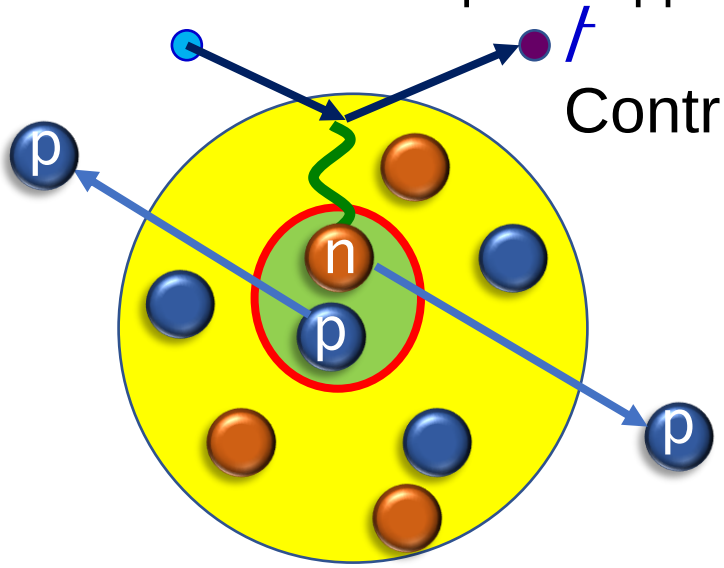
Charged current quasi-elastic scattering $\nu + n \rightarrow l^- + p$

Cross-section of CCQE-like events
Measured value is much larger than
the simple model predictions



(particle data book)

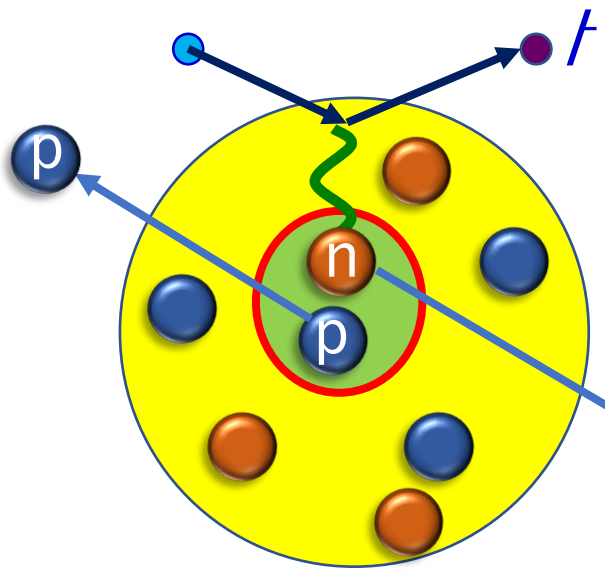
Due to the problem in the parameters
measured in the old experiments?
Is single nucleon scattering
with impulse approximation insufficient?



Contribution from 2 nucleon interaction?
Recent experiments did not measure
low momentum nucleons.
→ It is not possible to discriminate
single nucleon interaction
from multi-nucleon interactions.

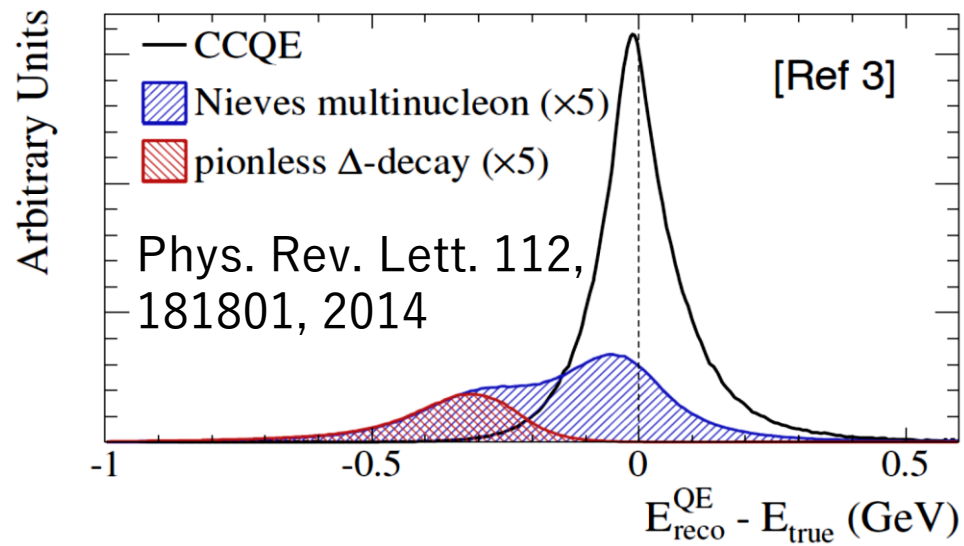
Interestingly, large suppression is observed
in the forward (small q^2) region.

Multi-nucleon interactions



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.

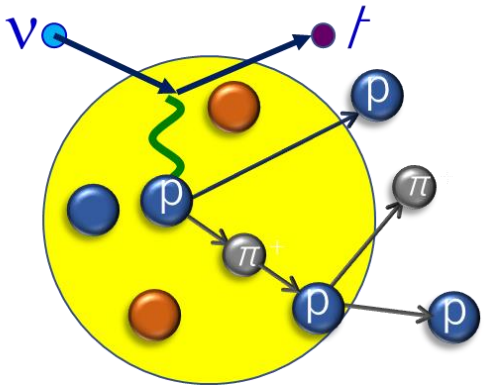


New experiments and theoretical studies to understand neutrino induced multi-nucleon scatterings have been started.

Nuclear effects ~ pion interaction in nucleus

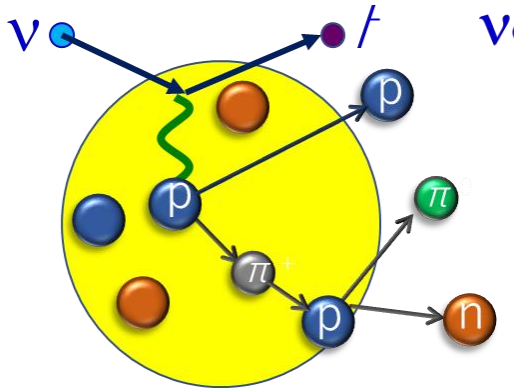
Pion interactions in nucleus is also important
because these interactions affect determination
of neutrino-nucleus interaction channel.

Inelastic scattering

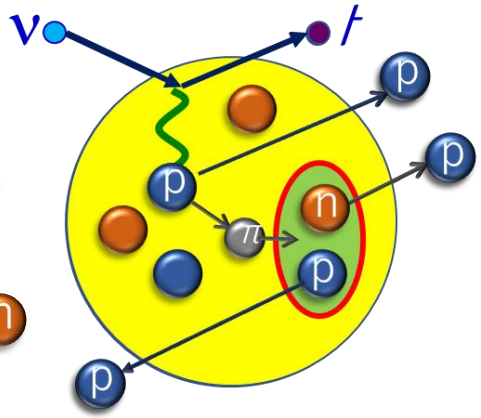


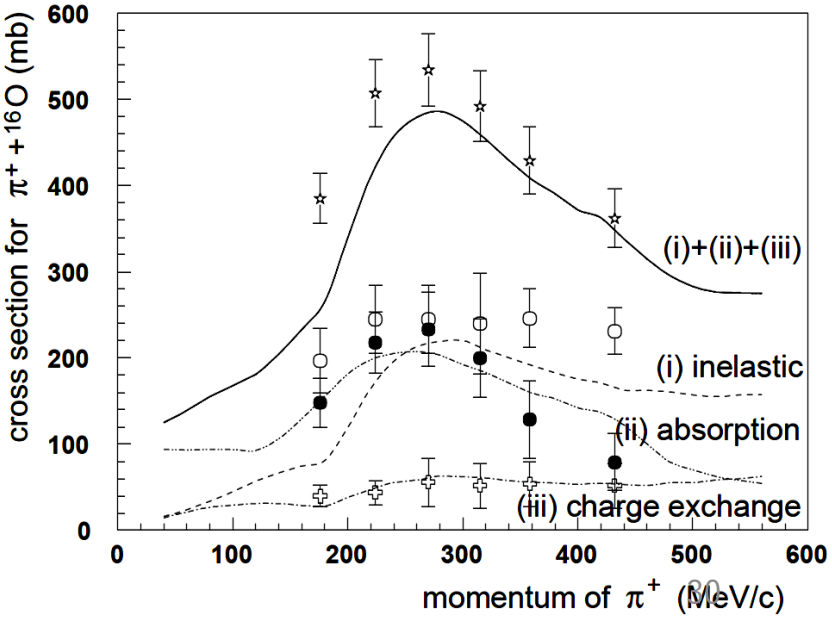
However, old data sets
have ***~ 30 %*** errors.
Also, a few data sets available
above Δ region.

Charge Exchange



Absorption

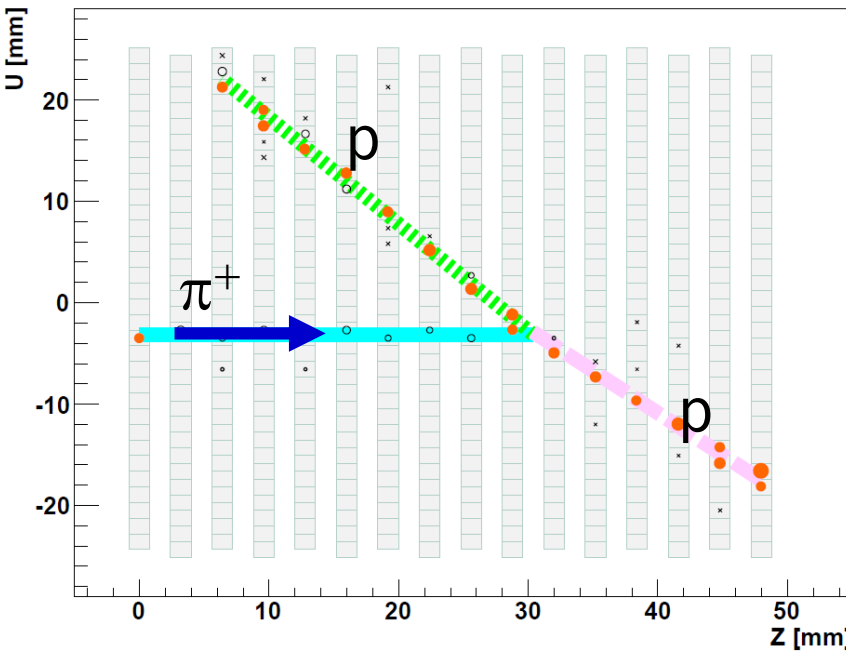




Nuclear effects ~ pion interaction in nucleus

DUET experiments used fiber tracker to measure
pion absorption & charge-exchange cross-sections.

Absorption candidate event



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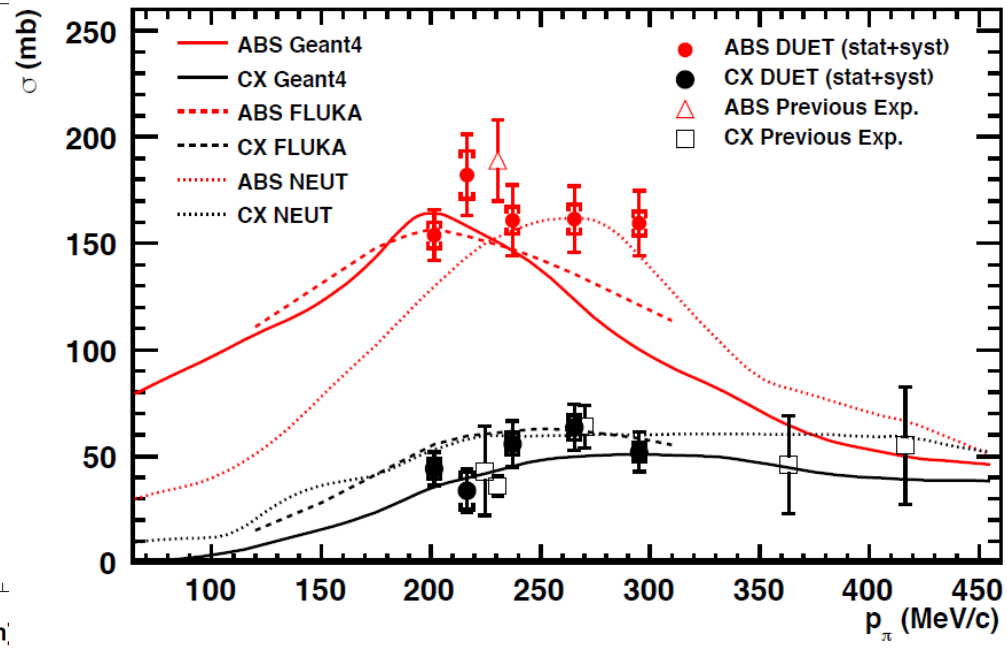

Almost back to back protons
are observed after absorption.
(Correlated pair nucleon absorbed π^+ ?)

Size of the error gets smaller.

Need higher precision measurements above delta region.

Summary

Study of neutrino oscillation using atmospheric and accelerator neutrinos heavily rely on the neutrino-nucleus scattering Monte-Carlo simulation programs.

Uncertainties from neutrino-nucleus scattering is one of the largest source of systematic errors.

It is necessary to reduce the errors for the discovery and parameter measurements of CP violation, mass hierarchy determination and precise determination of neutrino oscillation parameters.

PDF for low q^2 and low W and nuclear corrections, multi-nucleon interactions and pion interactions in nucleus will be important topics to be understood for the next generation experiments.

NuInt 18 - 12th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

15-19 October 2018
Gran Sasso Science Institute (GSSI)
Europe/Zurich timezone

Search...

https://indico.cern.ch/event/703880/

Since 2001, a series of workshop was started
to discuss neutrino-nucleus interactions
from both theoretical and experimental aspects.

This year, the 12th workshop will be held at
Gran Sasso Science Institute in Italy.
(October 15 ~ 19)

There will be a satellite meeting to discuss
Shallow and Deep inelastic scattering.
(October 11 ~ 13)

fin.