Current status of the neutrino-nucleus scattering experiments

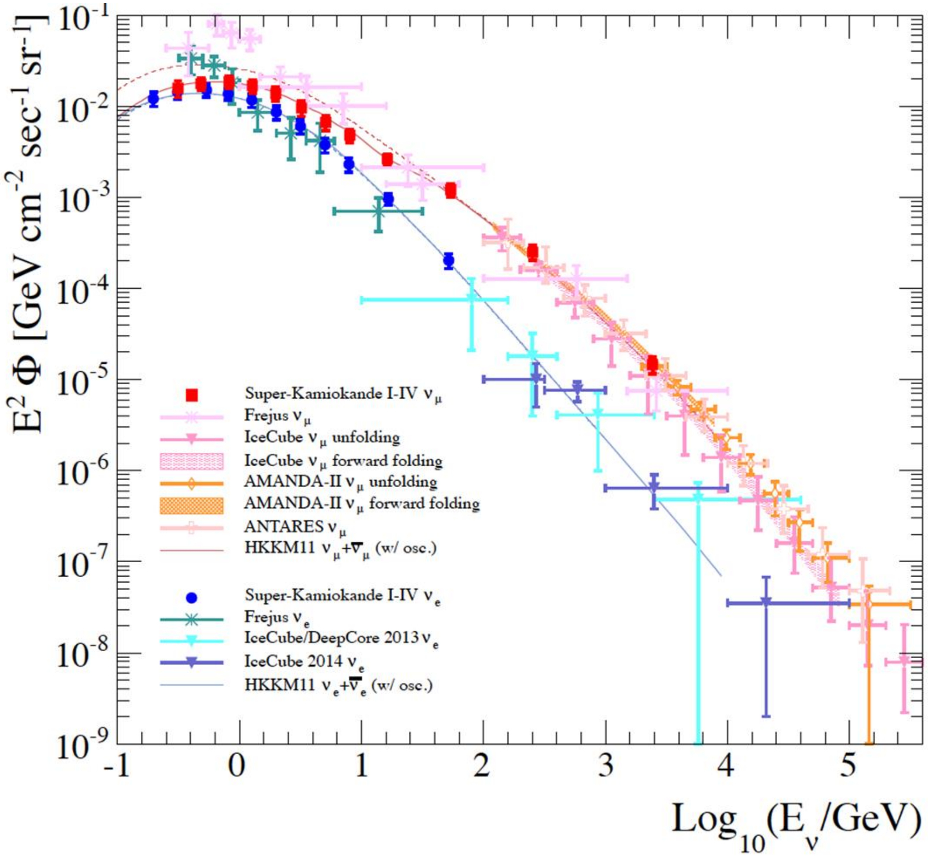
Yoshinari Hayato

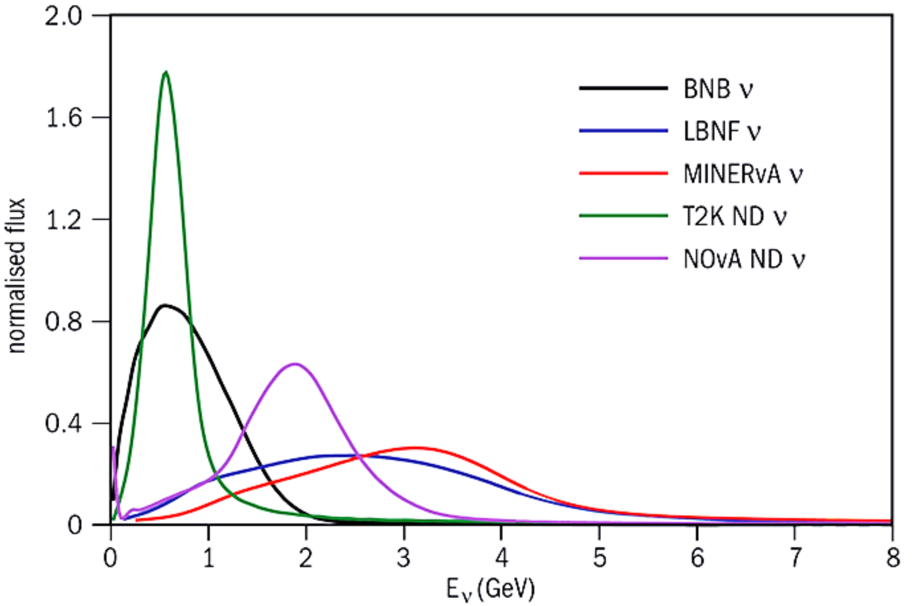
(Kamioka Obs., ICRR, The Univ. of Tokyo)

Study of neutrino properties using neutrino oscillation

Atmospheric ν 100 MeV ~ TeV
- Wide energy range
- Wide travel distance (baseline)
- All flavors $(\nu_e, \overline{\nu_e}, \nu_\mu, \overline{\nu_\mu})$

Accelerator ν 100 MeV ~ 10 GeV
- Narrower energy range
- Fixed travel distance (baseline)
- Mostly $(\nu_\mu, \overline{\nu_\mu})$ in the beam
  (Small fraction of ν_e and $\overline{\nu_e}$)





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

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

Single photon productions

$$\nu + N \rightarrow l^{-}(\nu) + N' + \gamma$$

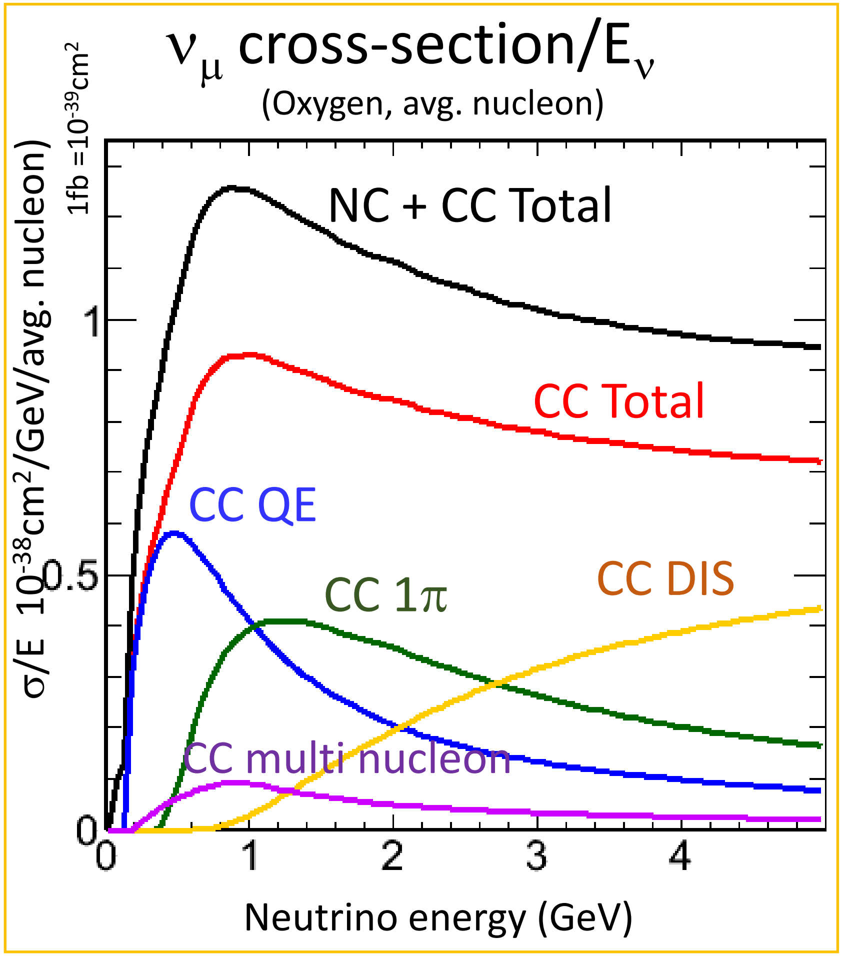
(radiative decay of resonance)

Deep inelastic scattering

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

Coherent Single meson productions

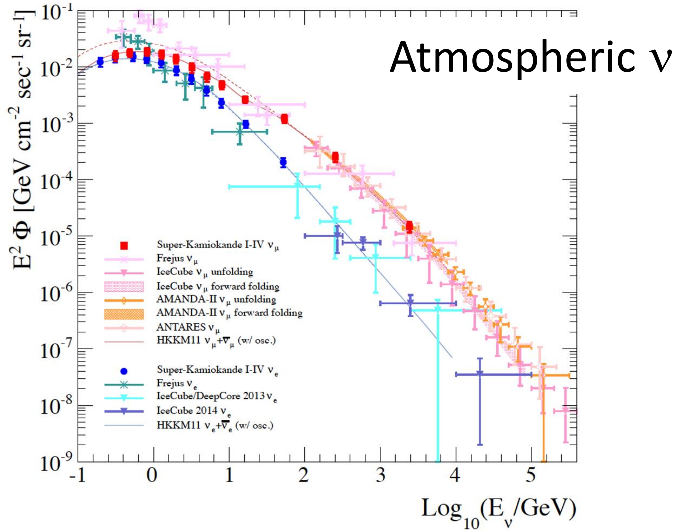
$$\nu + A \rightarrow l^{-}(\nu) + A' + \pi^{+}(\pi^{0})$$

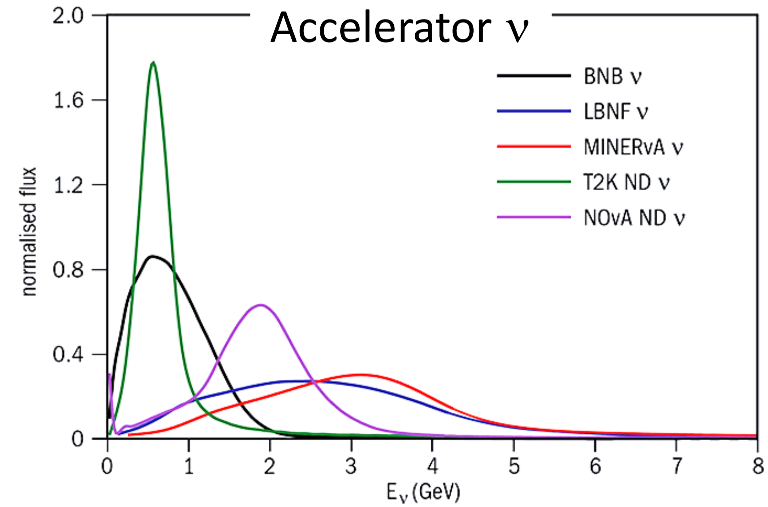


Neutrino detectors ~ nucleus target

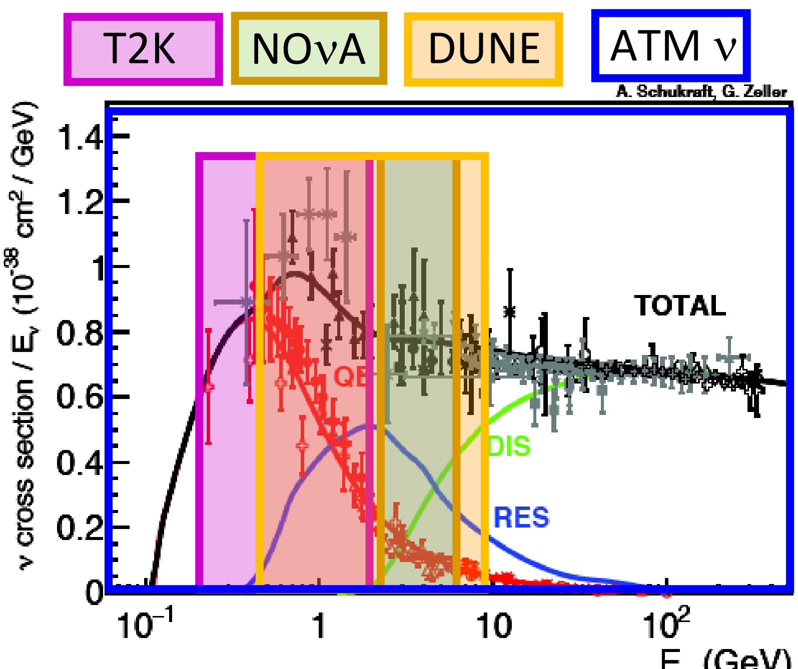
Various “nuclear effects” have to be taken into account.

Neutrino flux and neutrino interactions

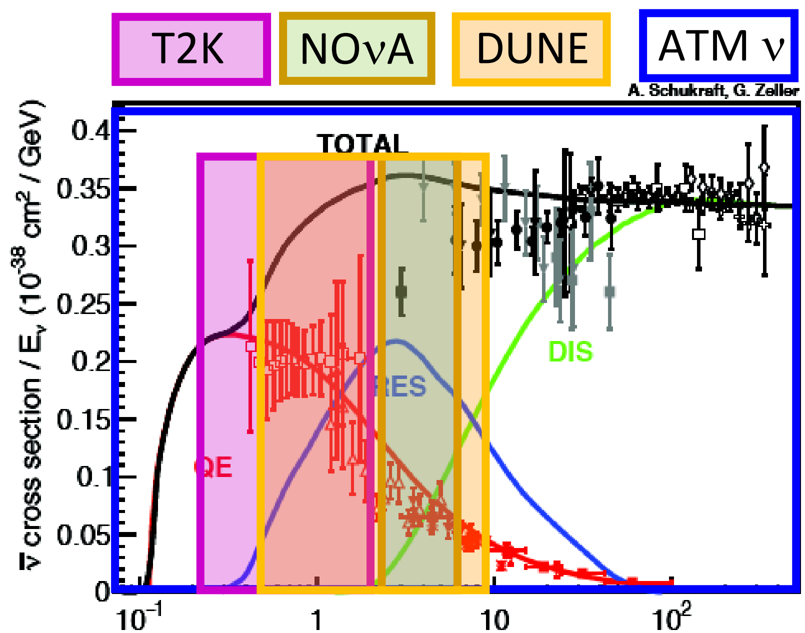




Neutrino cross-section



Anti-neutrino cross-section

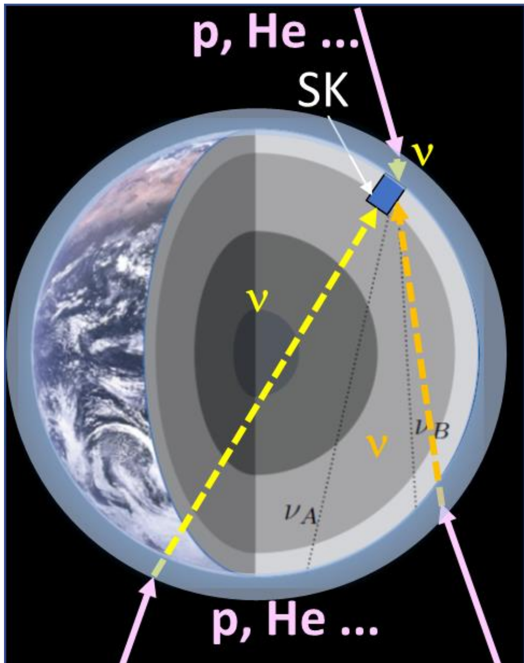


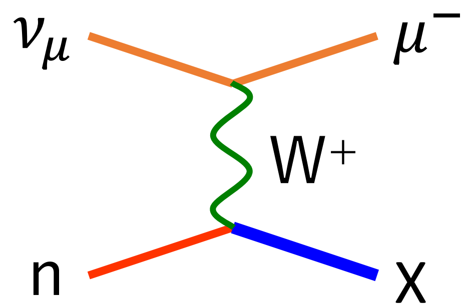
J. A. Formaggio, G. P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

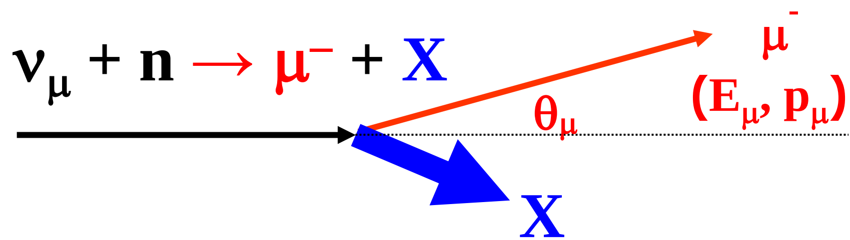
Methodology of neutrino oscillation experiments

Case 1: Atmospheric neutrinos, E_ν > 100MeV

Charged current interaction $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + X$



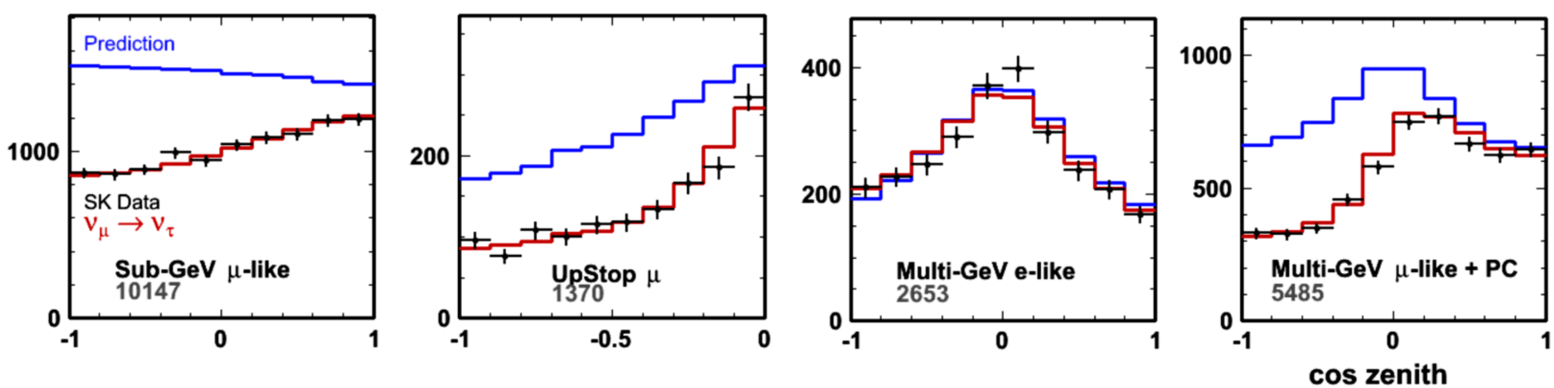




Compare the observed lepton momentum and directions with the “expected” distributions with various oscillation parameters.

(few exceptions)

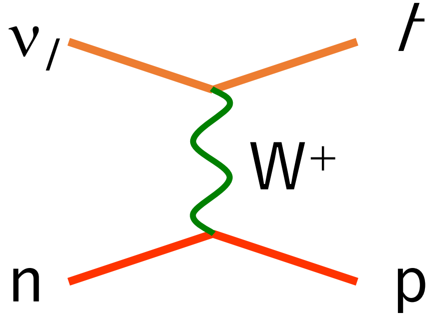
Zenith angle distribution of various samples

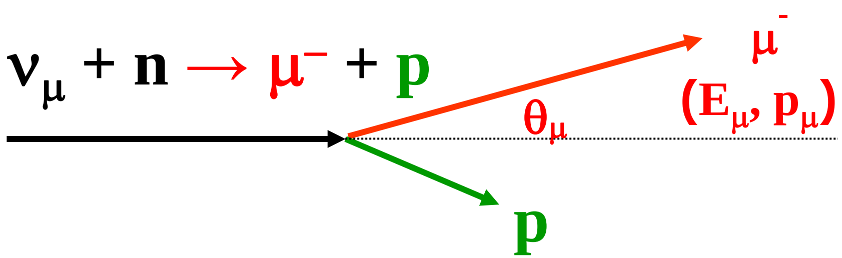


Methodology of neutrino oscillation experiments

Case 2: Accelerator neutrinos, E_ν = 100MeV ~ a few GeV

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

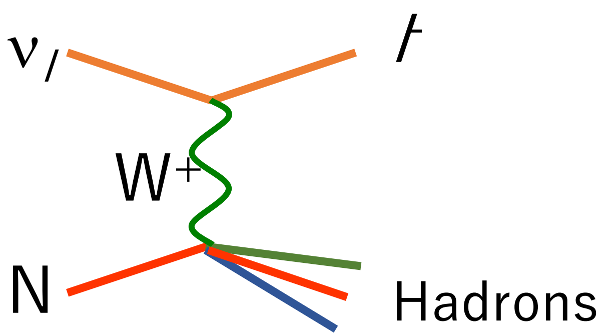
Methodology of neutrino oscillation experiments

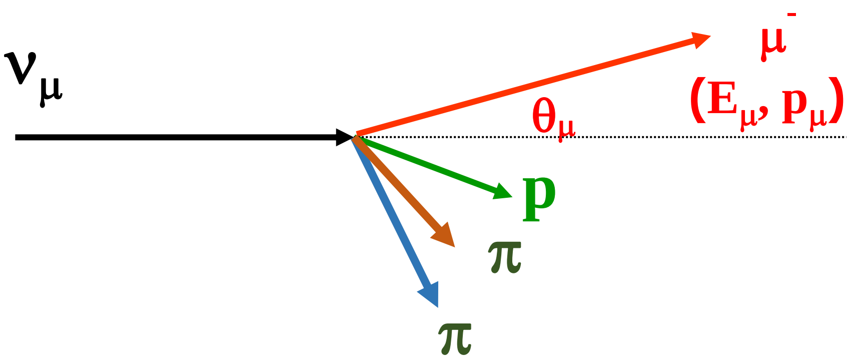
Case 3: Accelerator neutrinos, E_ν > several GeV

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

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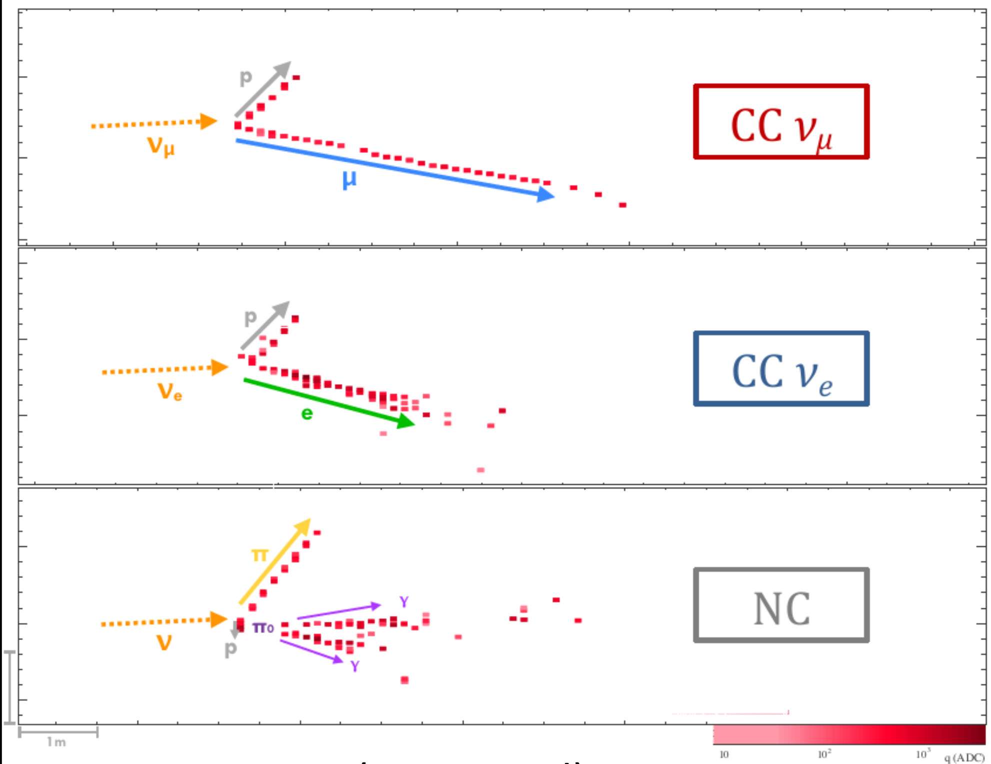
(Charged current deep/shallow inelastic scattering)

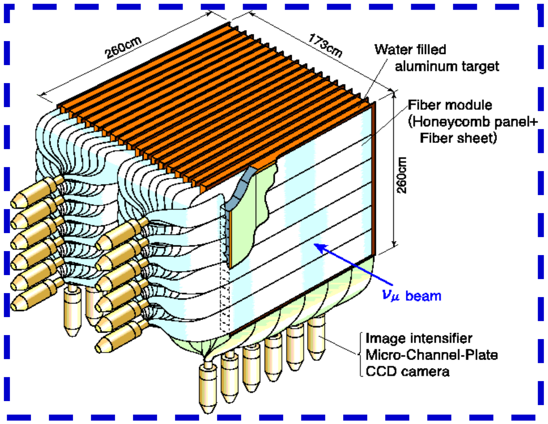


(A. Himmel)

- Identify neutrino flavor using a **convolutional neural network.**
  - A deep-learning technique from computer vision
  - New, faster network for 2020.
- Before main PID:
  - Events are contained in the detector
  - CC ν_μ require a well-reconstructed μ track
  - Reject cosmic rays with BDTs
- Performance relative to preselection:
  - ν_μ: ~90% efficient, 99% bkg. rejection
  - ν_e: ~80% efficient, 80% bkg. rejection
- Validate performance against data-driven control samples in both detectors.

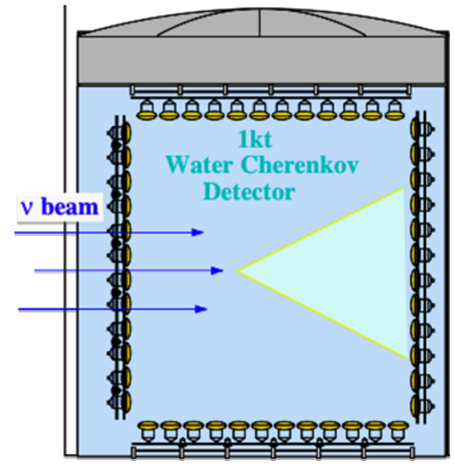
Neutrino-nucleus scattering experiments

1998 ~ neutrino-nucleus interactions are studied (again)
for long baseline neutrino oscillation measurements

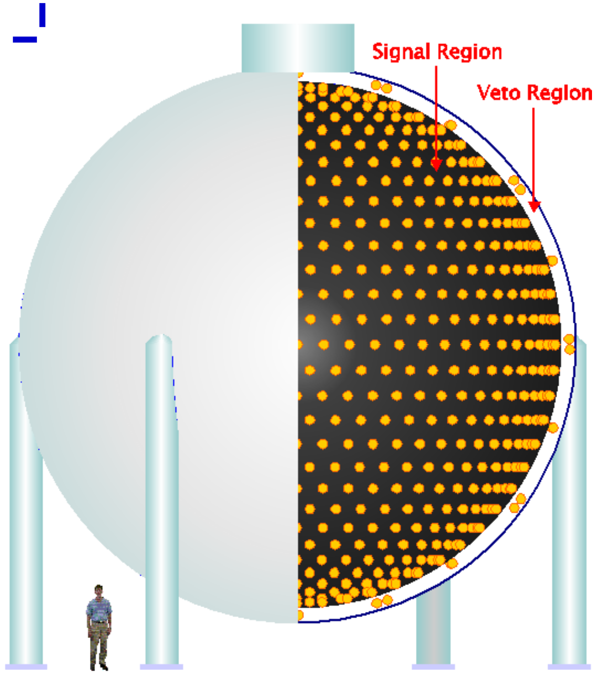


Scintillation fiber tracker with water container@K2K (SciFi @ KEK, K2K)

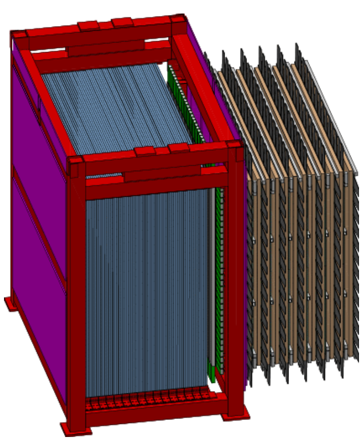
1kt Water Cherenkov detector (@ KEK, K2K)



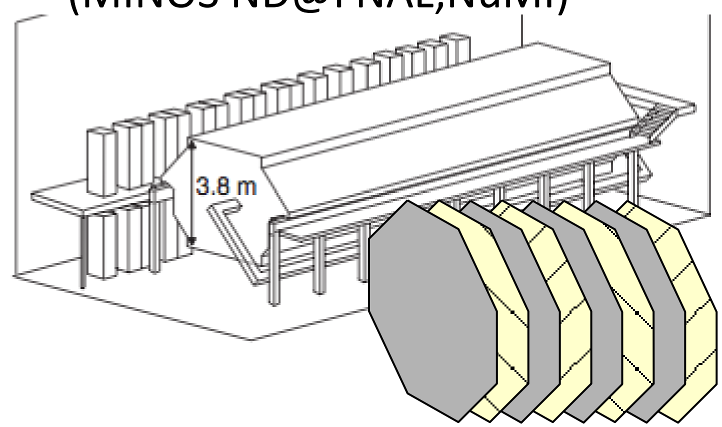
Oil Cherenkov detector (MiniBooNE@FNAL, BNB)



Full active scintillator tracking detector (SciBar@FNAL, BNB)



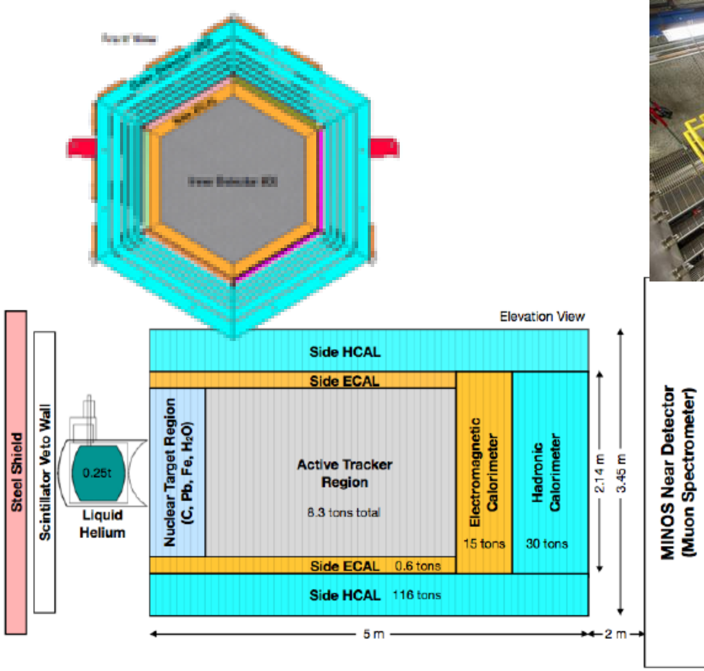
Scintillator + Iron tracking detector (MINOS ND@FNAL,NuMI)



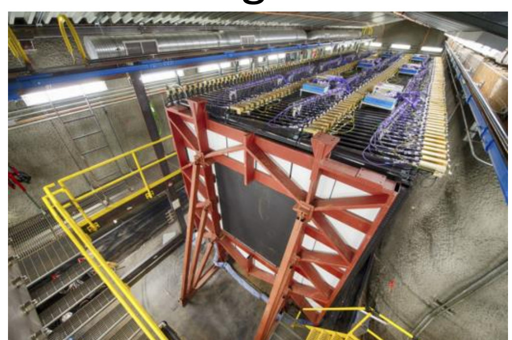
More experiments ~ higher power neutrino beam

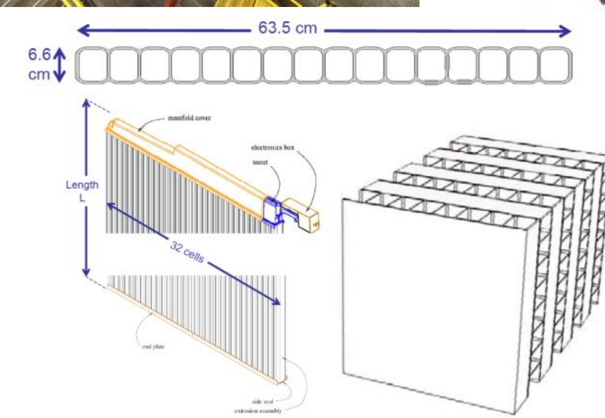
- Precise measurement
  - High statistics (with intense neutrino beam)
  - Low momentum particle (hadron) detection/tracking
- Nuclear dependence

MINERνA (@FNAL, NuMI)
Full active detector
+ various nuclear target
+ MINOS ND

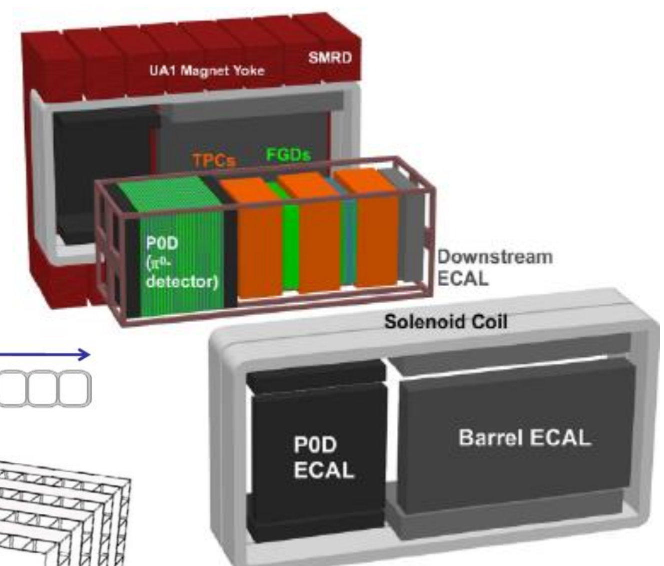


NOνA (@FNAL, NuMI)
Full active scintillator tracking detector





T2K ND280 (@J-PARC, T2K)
Full active scintillator tracker, TPC, Calorimeter



Various issues of neutrino-nucleus interaction

Various discrepancies were found.

Simulation programs (models in the simulation programs) can not reproduce the data.

- Fewer # of events with the forward going muons

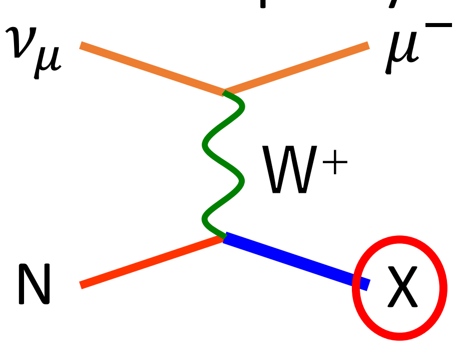
  Forward going muons ~ small energy transfer

  Possibilities

  Nuclear modeling

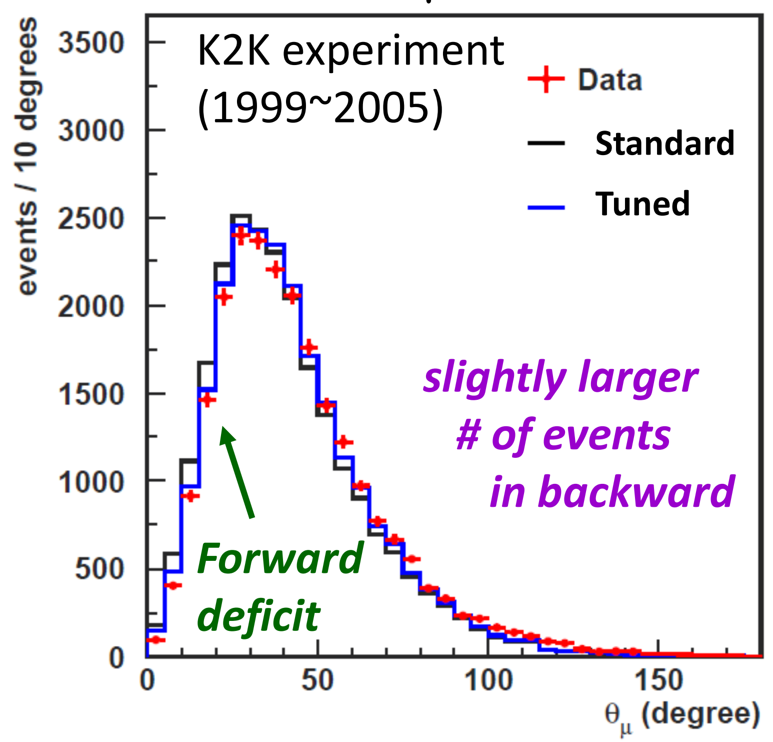
  Neutrino interaction models

→ Need to identify the source of the discrepancy.



Need hadron information

Direction of μ w.r.t. beam



Various issues of neutrino-nucleus interaction

Various discrepancies were found.

Simulation programs (models in the simulation programs) can not reproduce the data.

- # of “CCQE-like” events are larger than expected (10 ~ 20%)

  Possibilities

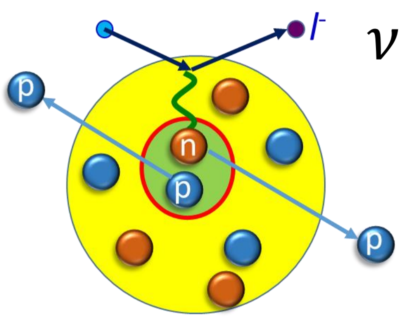
  Neutrino interaction cross-section underestimation

  Missing (not simulated) interaction channel

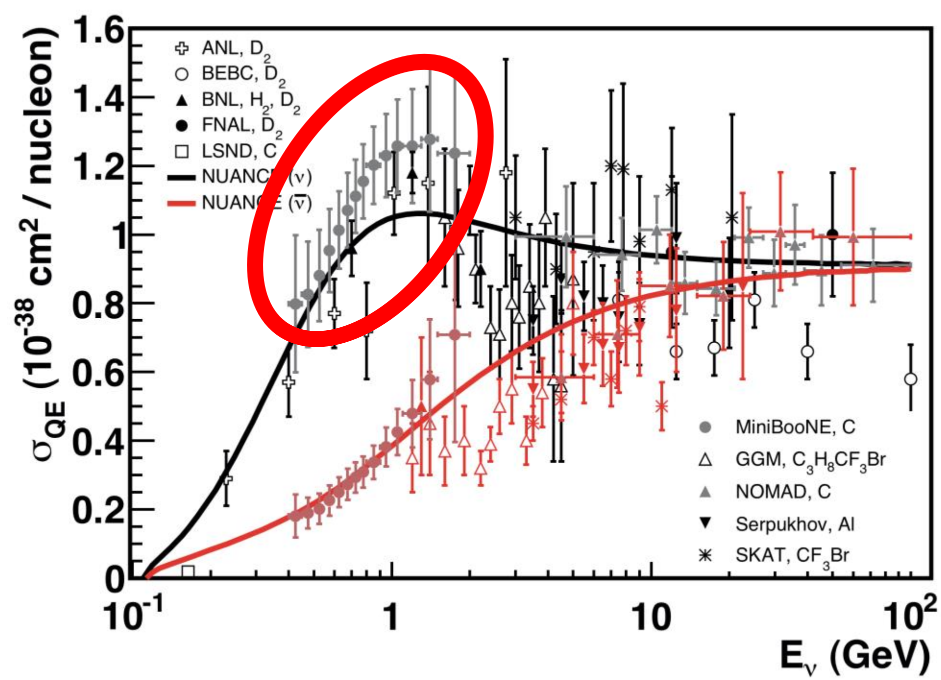
These measurement did not observe (identify) hadrons.

➢ Limitation from the detector capability.

“multi-nucleon” scattering (?)



$$\nu\, N_1 N_2 \rightarrow l^{\pm}\, N_1' N_2'$$



Various issues of neutrino-nucleus interaction

Various discrepancies were found.

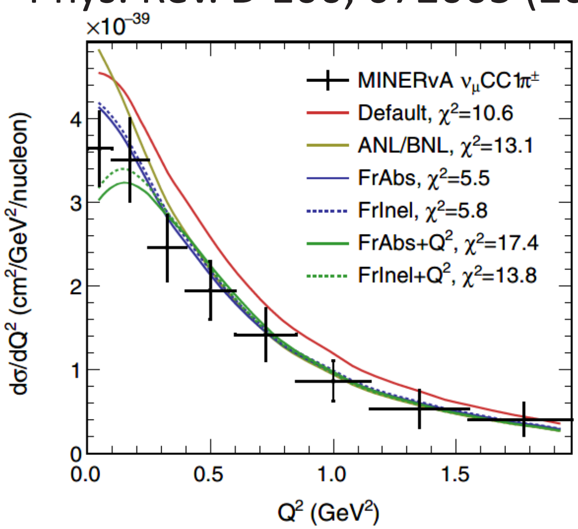
Simulation programs (models in the simulation programs) can not reproduce the data.

- Charged current single π production

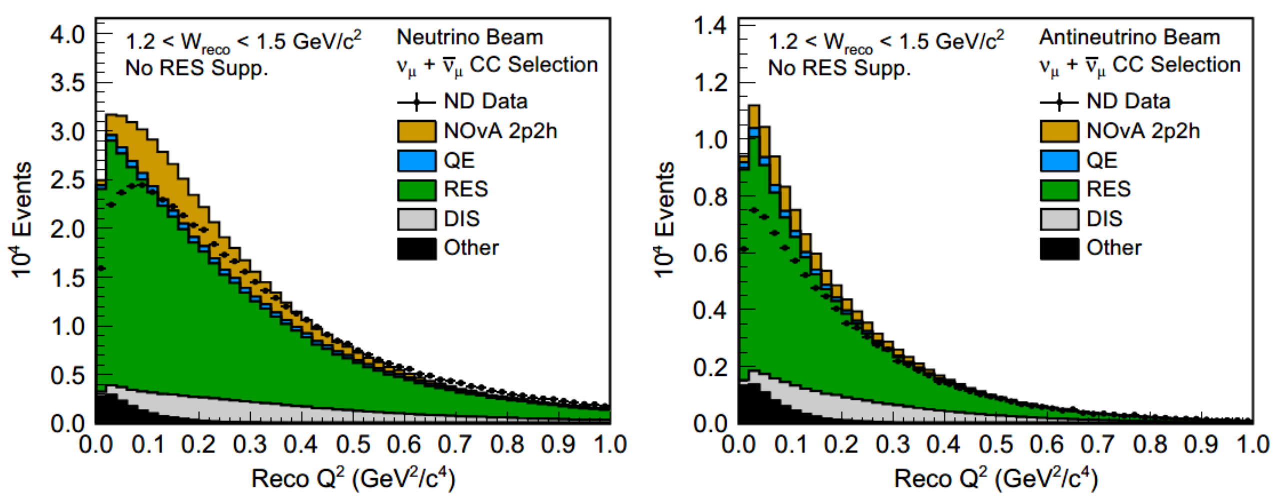
$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi\ (\ \eta, K\ )$$

  - Suppression in small q^2
  - Discrepancy of π momentum distribution

MINERνA
Phys. Rev. D 100, 072005 (2019)



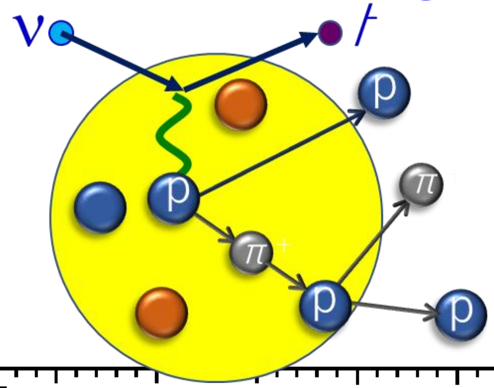
NOνA
Eur. Phys. J. C (2020) 80:1119



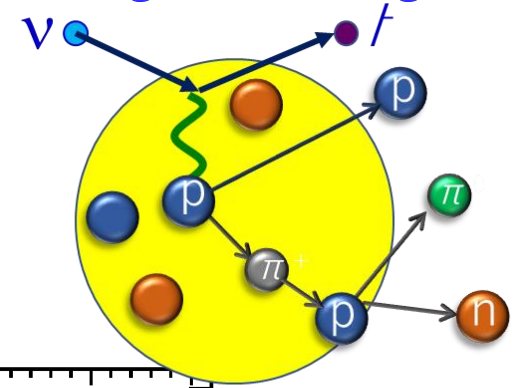
Various issues of neutrino-nucleus interaction

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

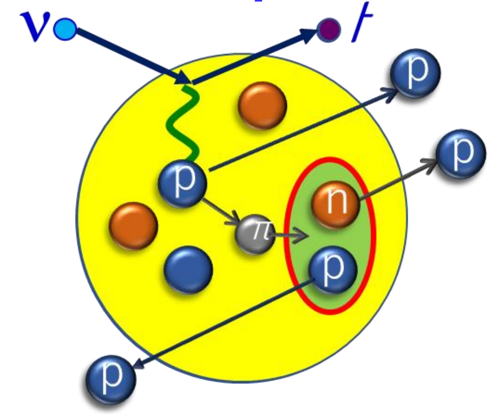
Inelastic scattering

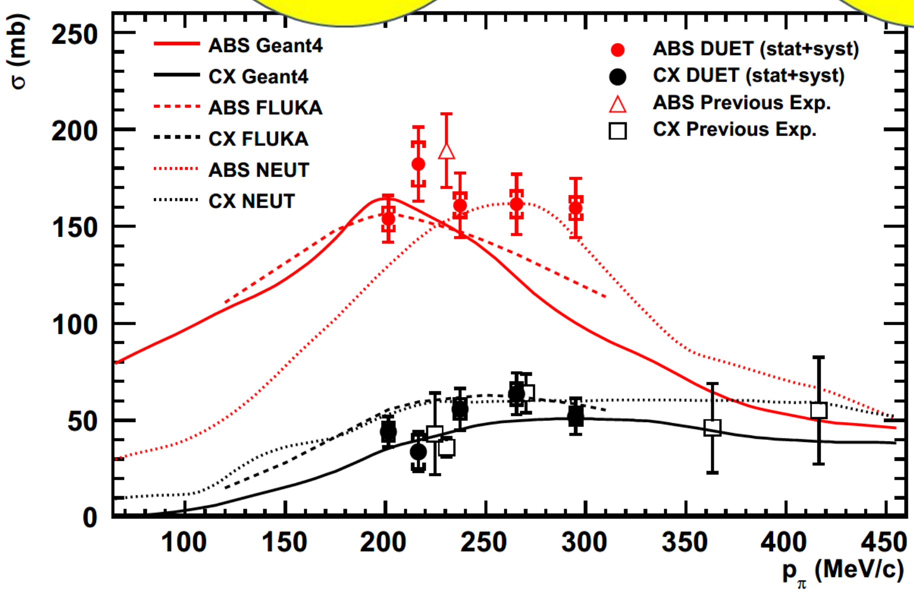


Charge Exchange



Absorption



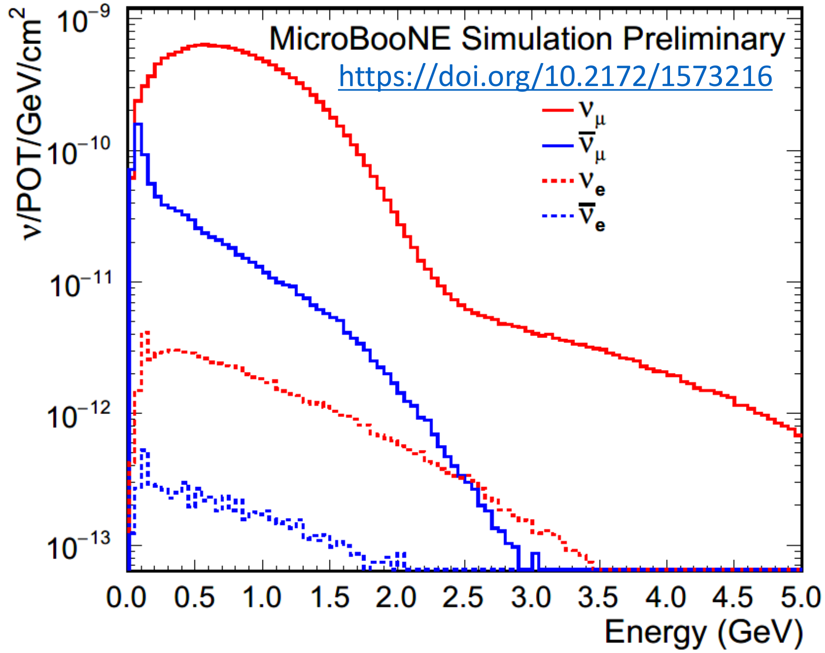


However,
available data sets are limited
and
few data above Δ region
(p_π > 350 MeV/c).

➢ Source of uncertainty.

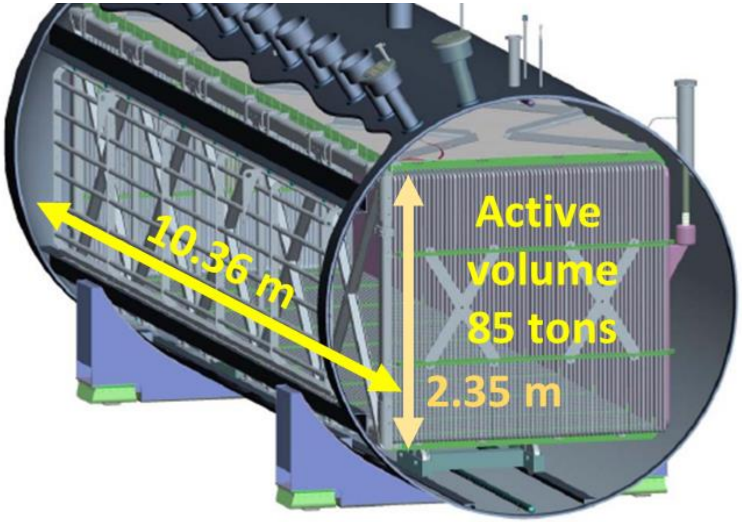
New high-resolution experiments #1; MicroBooNE

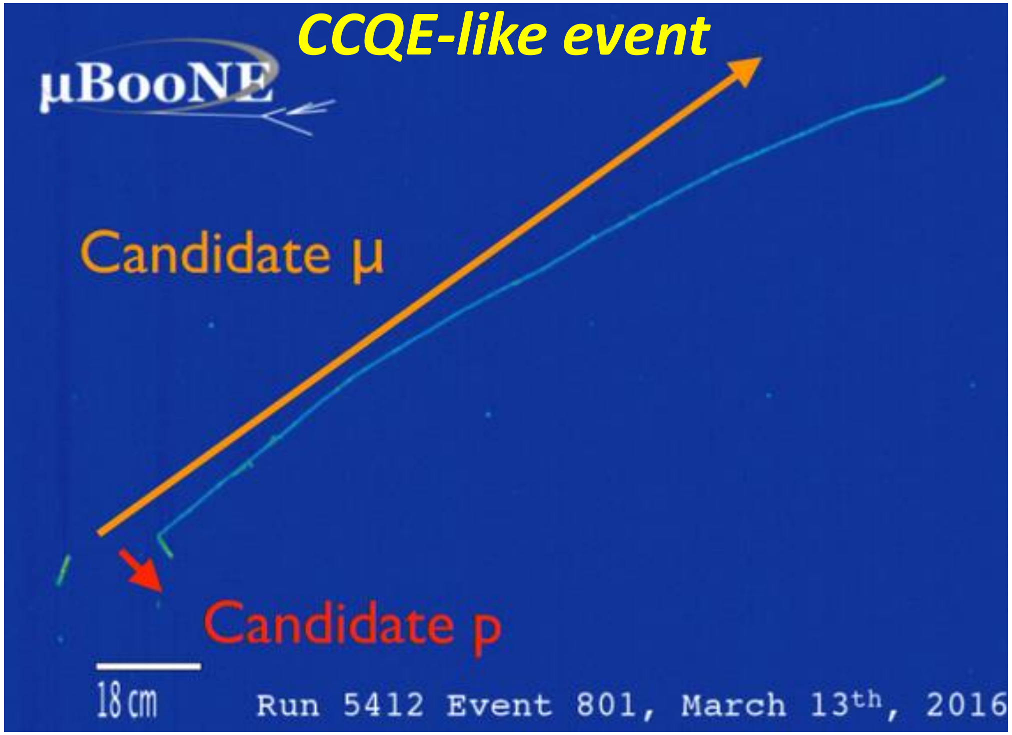
MicroBooNE @ FNAL, BNB (Liquid Argon TPC)



Neutrino energy is < 1 GeV
CCQE dominant region

Low proton momentum threshold
~ 300 MeV/c (E_k ~ 47 MeV)



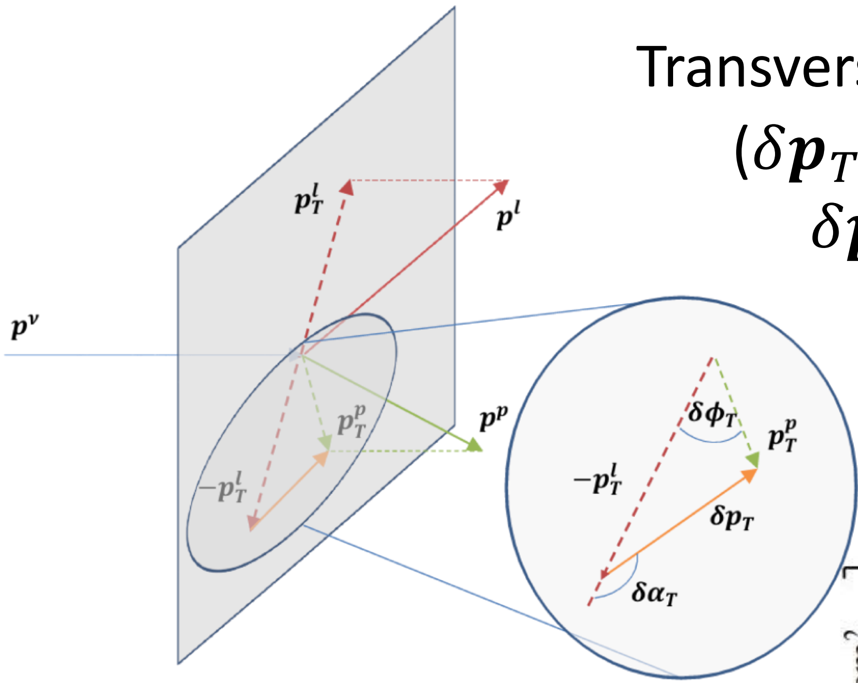


Recent measurement of "nuclear effects" (MicroBooNE)

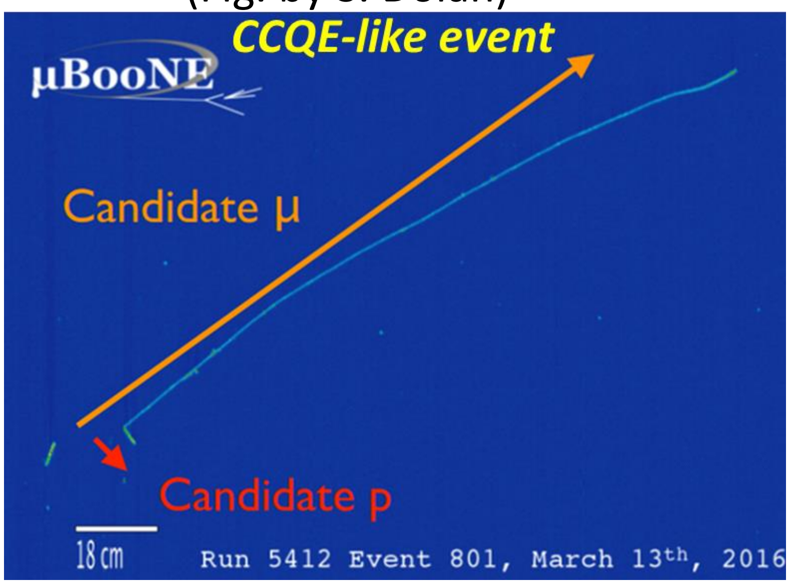
Transverse momentum valance

$(\delta \boldsymbol{p}_T = \boldsymbol{p}_T^p + (-\boldsymbol{p}_T^l))$

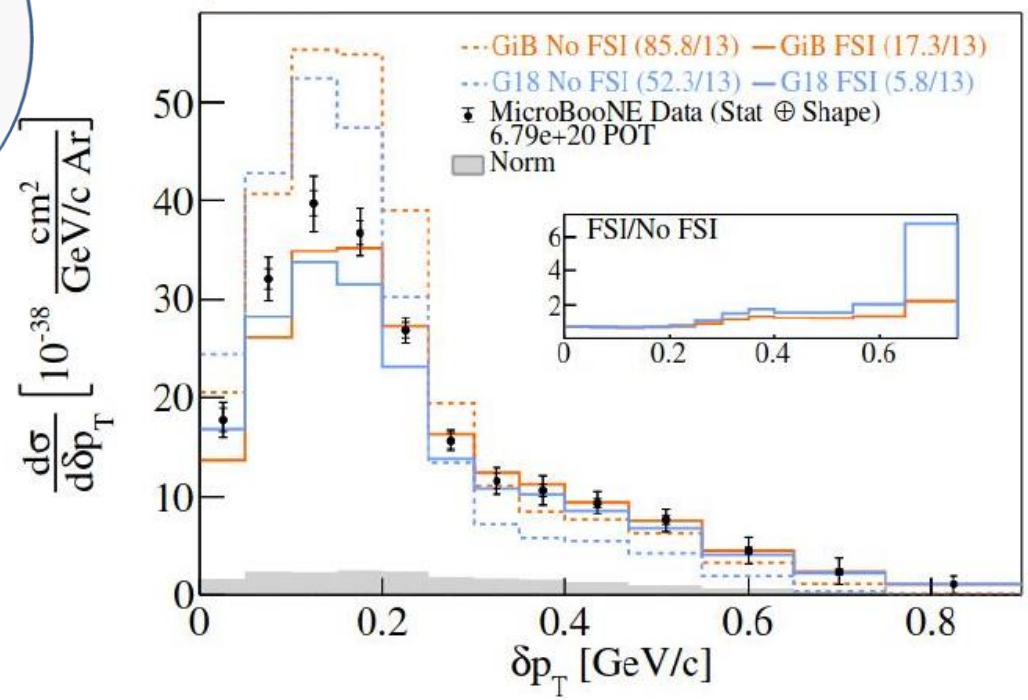
$\delta \boldsymbol{p}_T = 0$ if initial nucleon is stopped and there is no binding effect.



(Fig. by S. Dolan)



MicroBooNE : Argon target

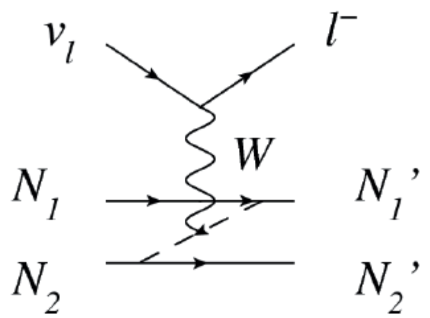


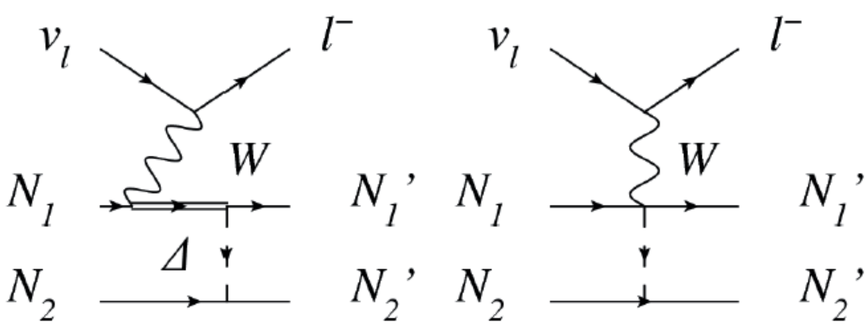
https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1108-PUB.pdf

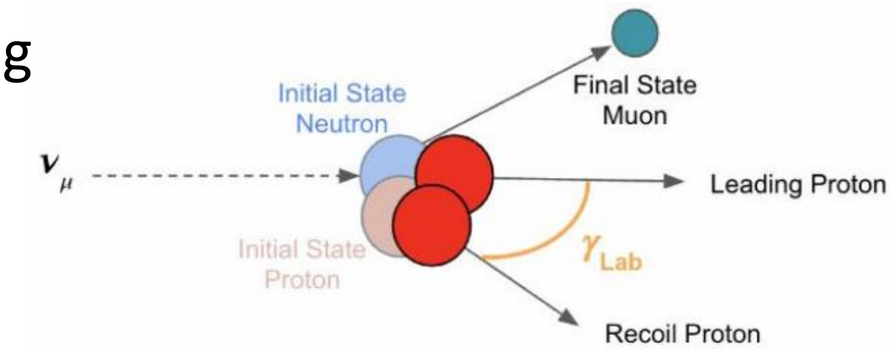
Recent measurement of multi-nucleon interaction (MicroBooNE)

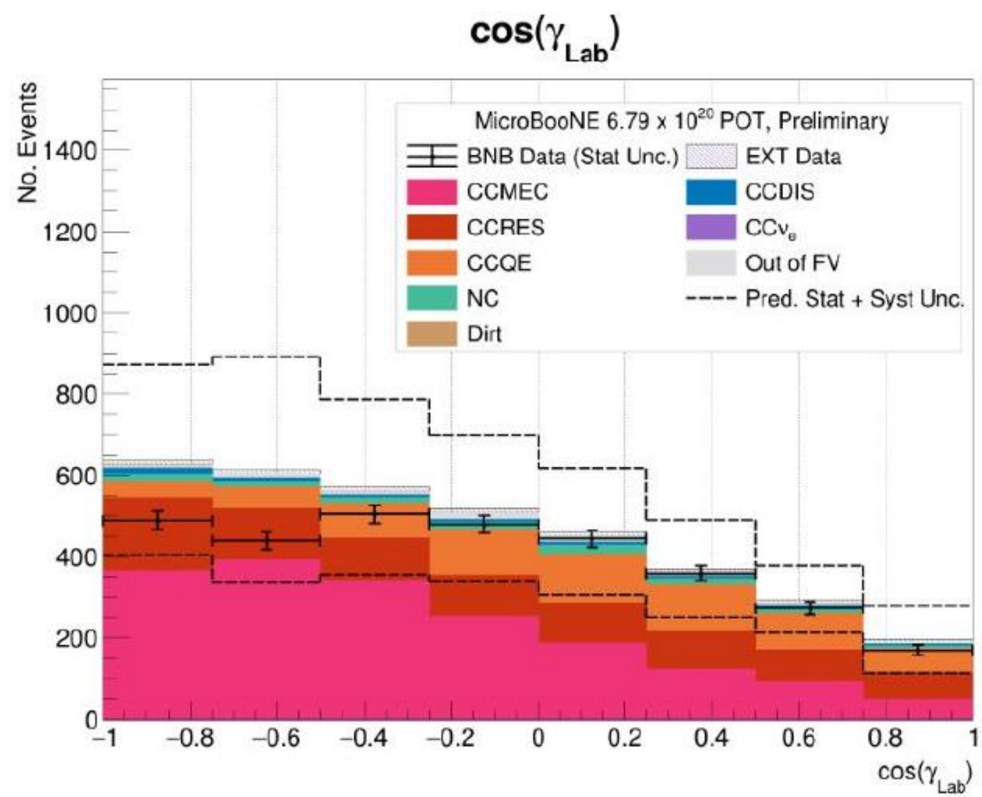
"multi-nucleon" CCQE-like scattering

$$\nu\, N_1 N_2 \rightarrow l^{\pm}\, N_1' N_2'$$









Two "correlated" nucleons are predicted to be emitted back-to-back.

-> measure γ_{LAB}

https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1117-PUB.pdf

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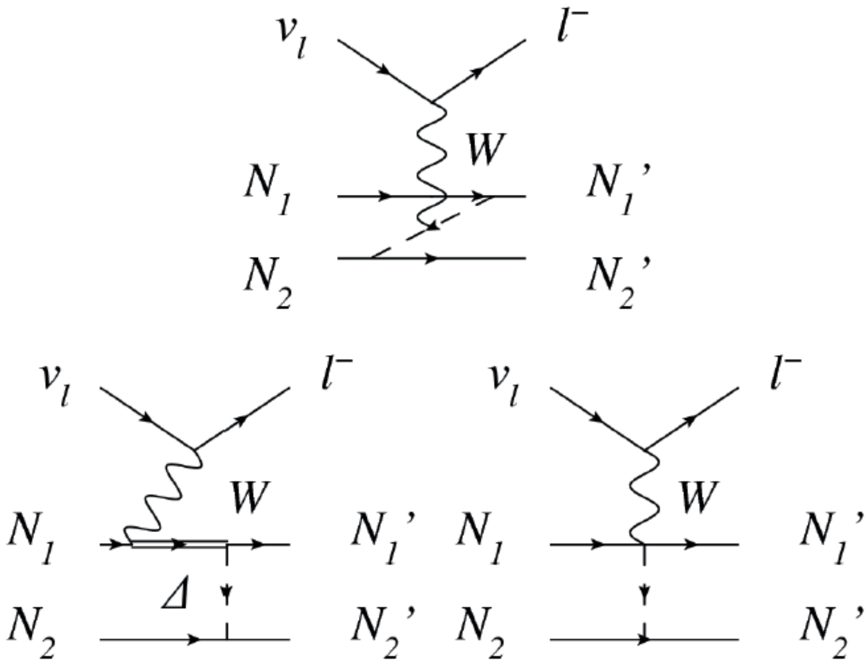

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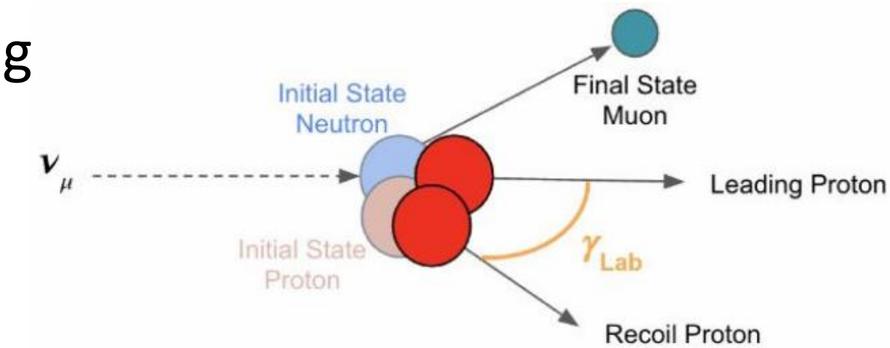
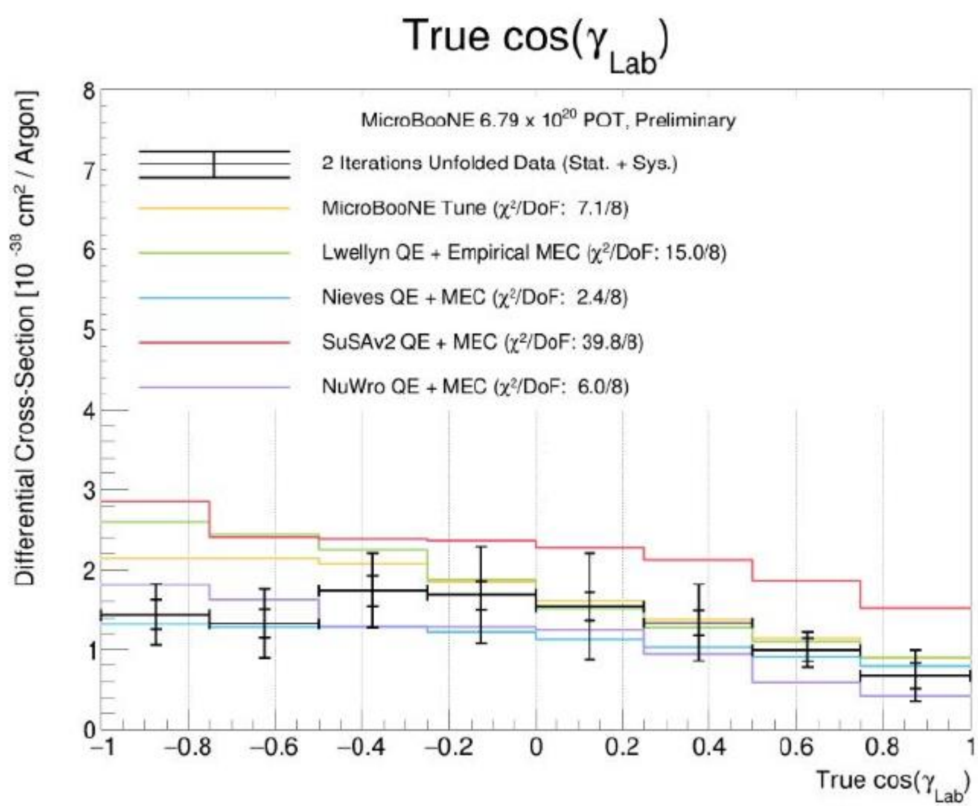
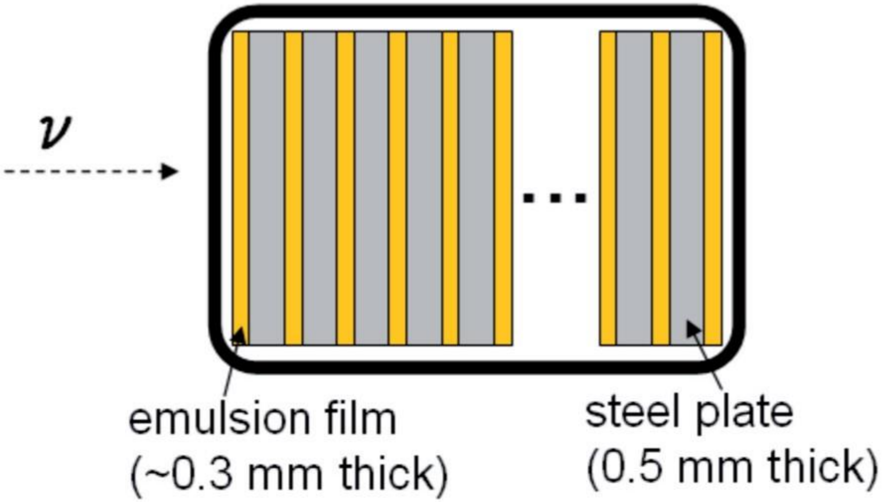




https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1117-PUB.pdf

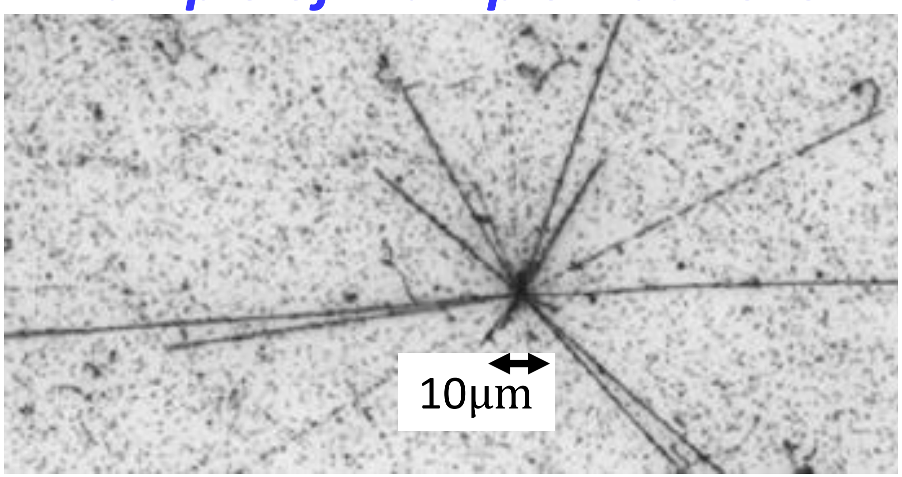
New high-resolution experiments #2; Ninja

Nuclear emulsion detector



41 emulsion films + 40 steel plates

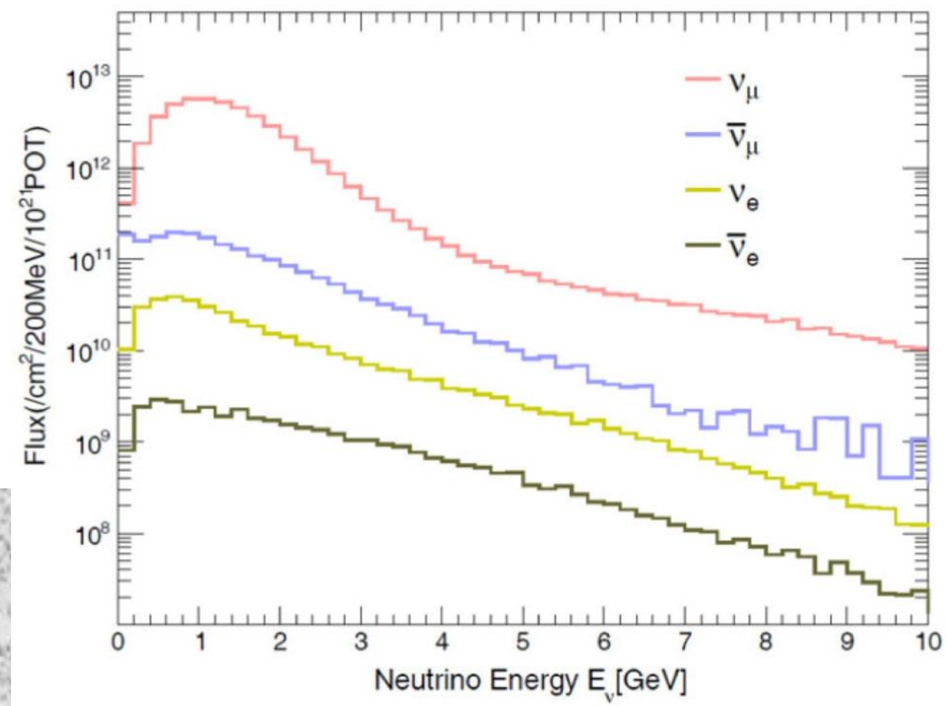
Example of multiple track event



Ninja @ J-PARC, T2K neutrino beamline

Mean E_ν ~ 1.49 GeV

CCQE & single π production



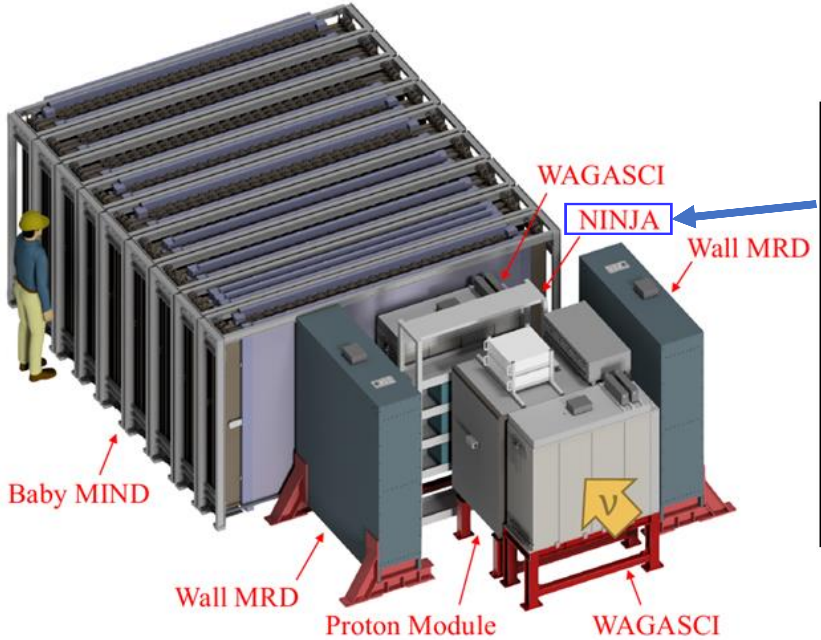
Low hadron momentum threshold

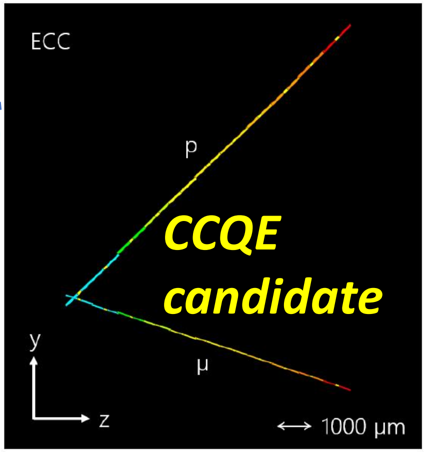
Proton ~ 200 MeV/c

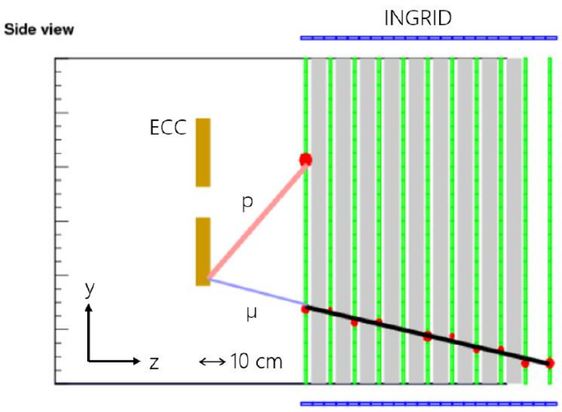
Charged pion ~ 50 MeV/c

New high-resolution experiments #2; Ninja

Nuclear emulsion detector   Ninja @ J-PARC, T2K



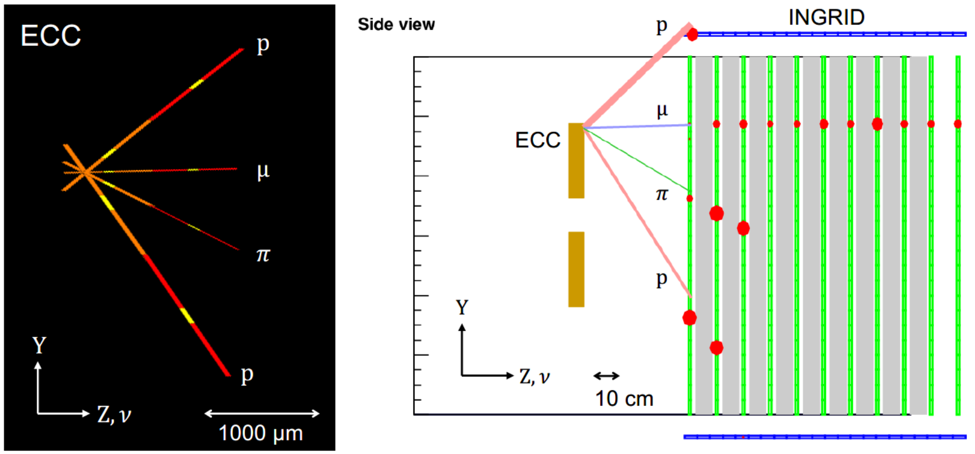




Main emulsion detector does not provide timing information.
Also, the size is small, and particles escapes from the detector easily.
Need to be combined with the other time stamper
and tracking detectors.

Recent measurement of hadrons from neutrino interactions (Ninja)

$\nu_\mu + {}^{56}Fe$ Average $E_\nu \sim 1.5$GeV



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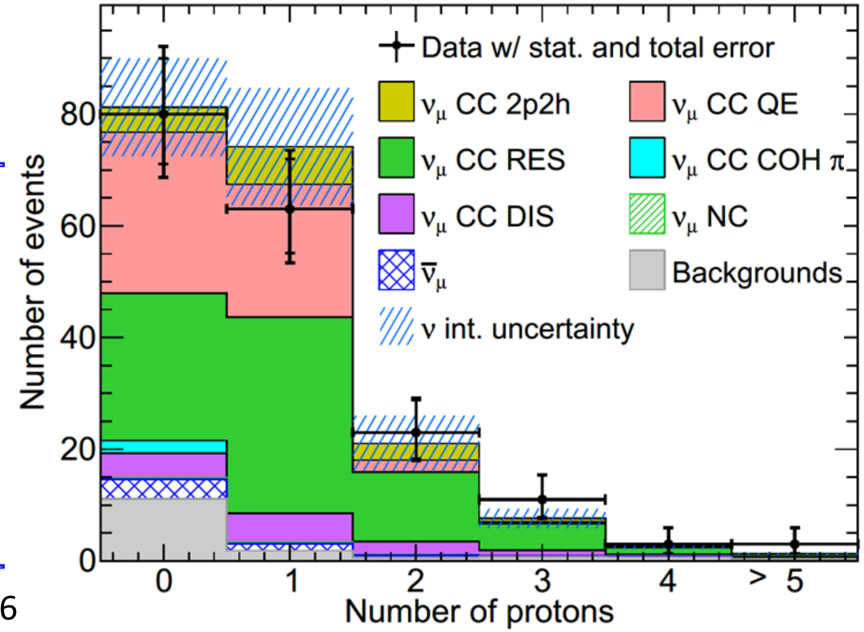
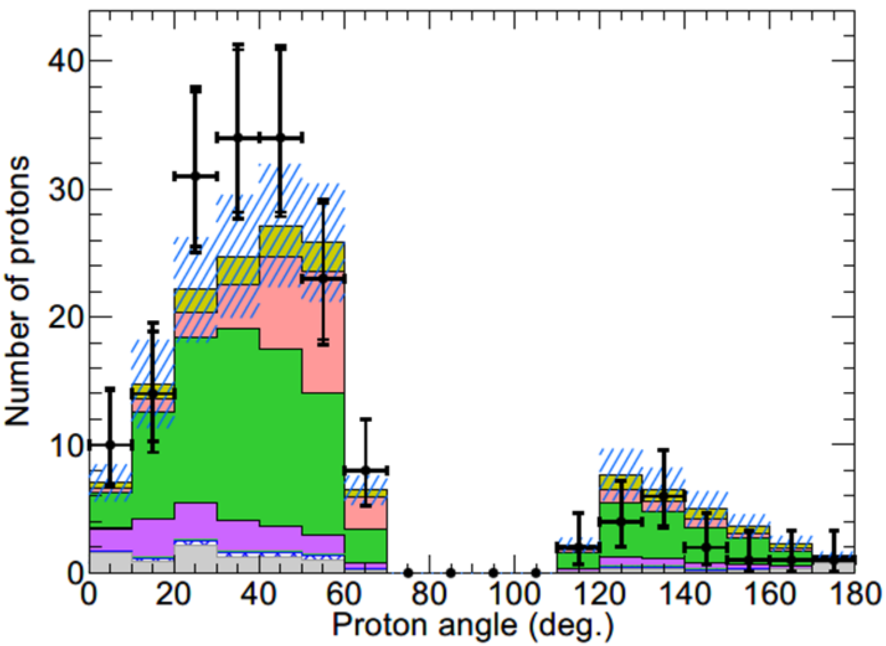
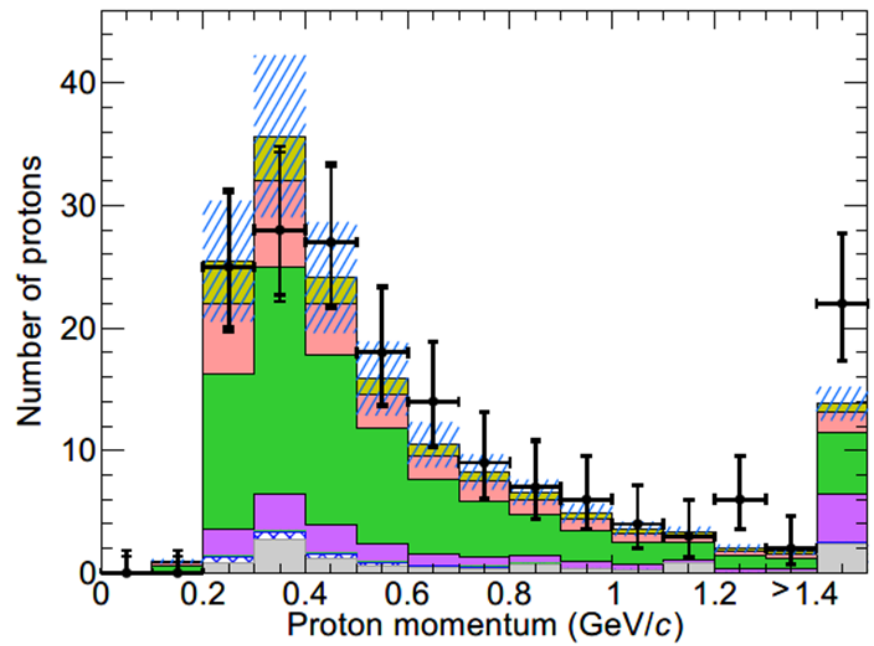






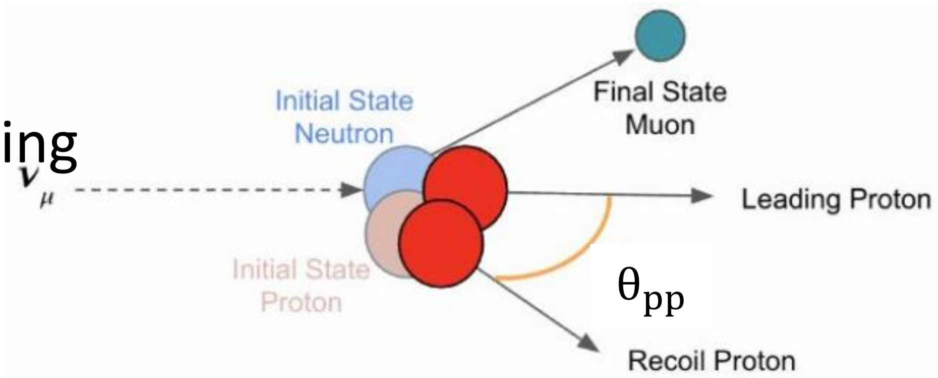
Recent measurement of hadrons from neutrino interactions (Ninja)

ν_μ + ^{56}Fe   Average $E_\nu \sim 1.5\mathrm{GeV}$

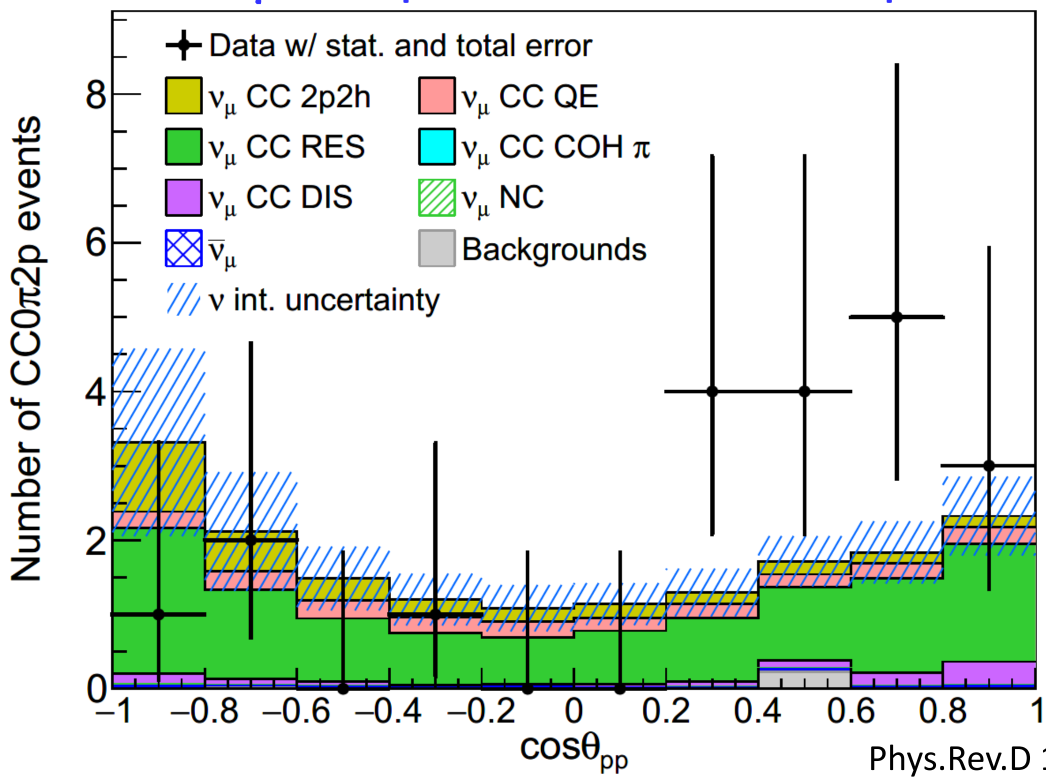
"multi-nucleon" CCQE-like scattering

$$\nu\, N_1 N_2 \rightarrow l^{\pm}\, N_1' N_2'$$

+ Hadron (pion) "rescattering"



1 μ + 2 protons event sample



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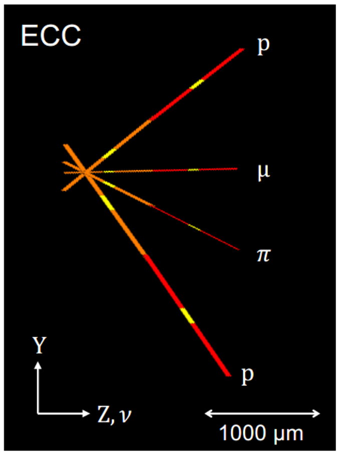

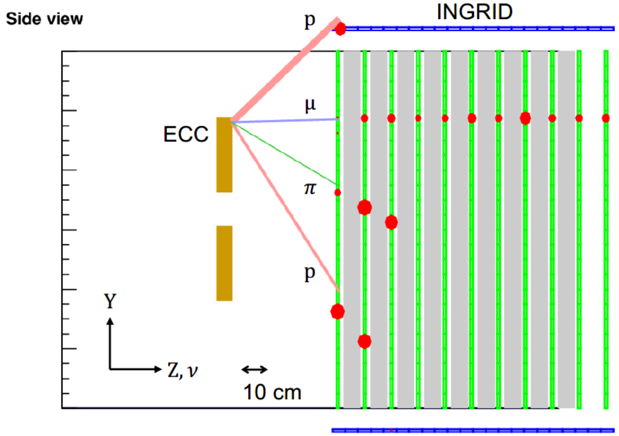

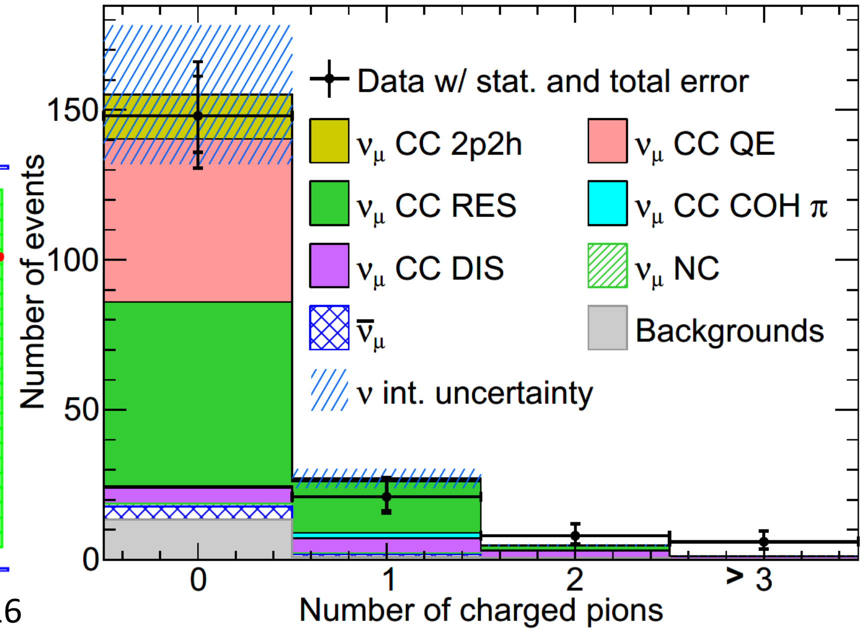

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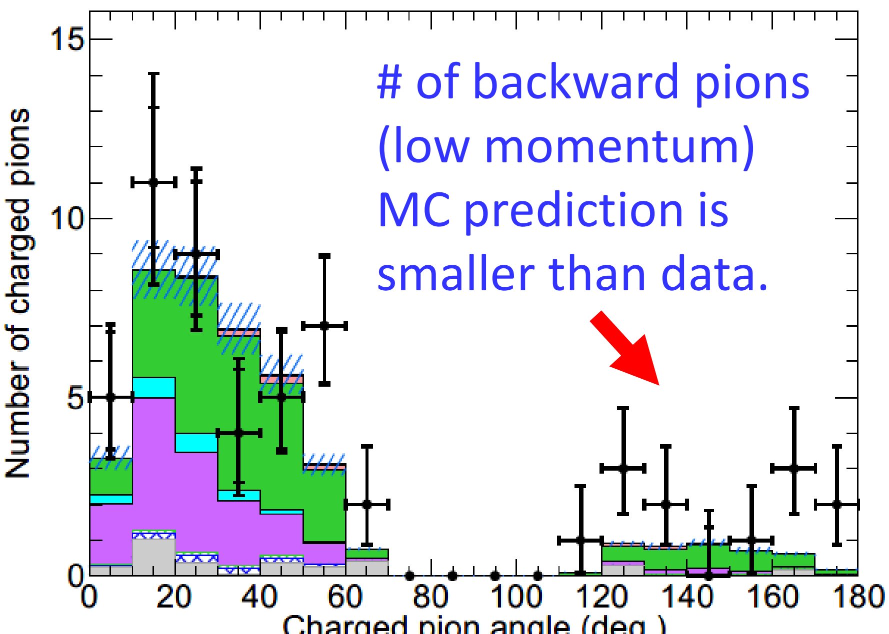
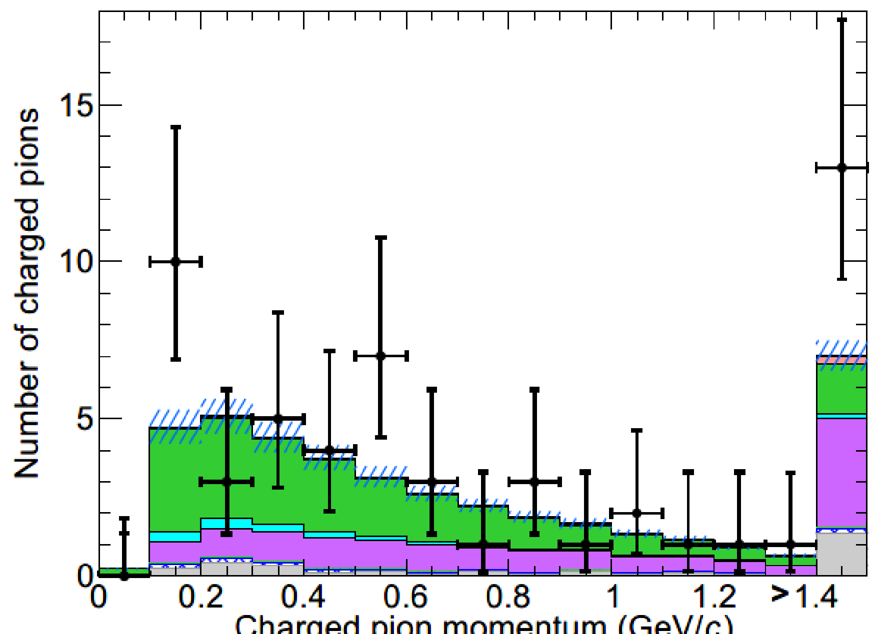
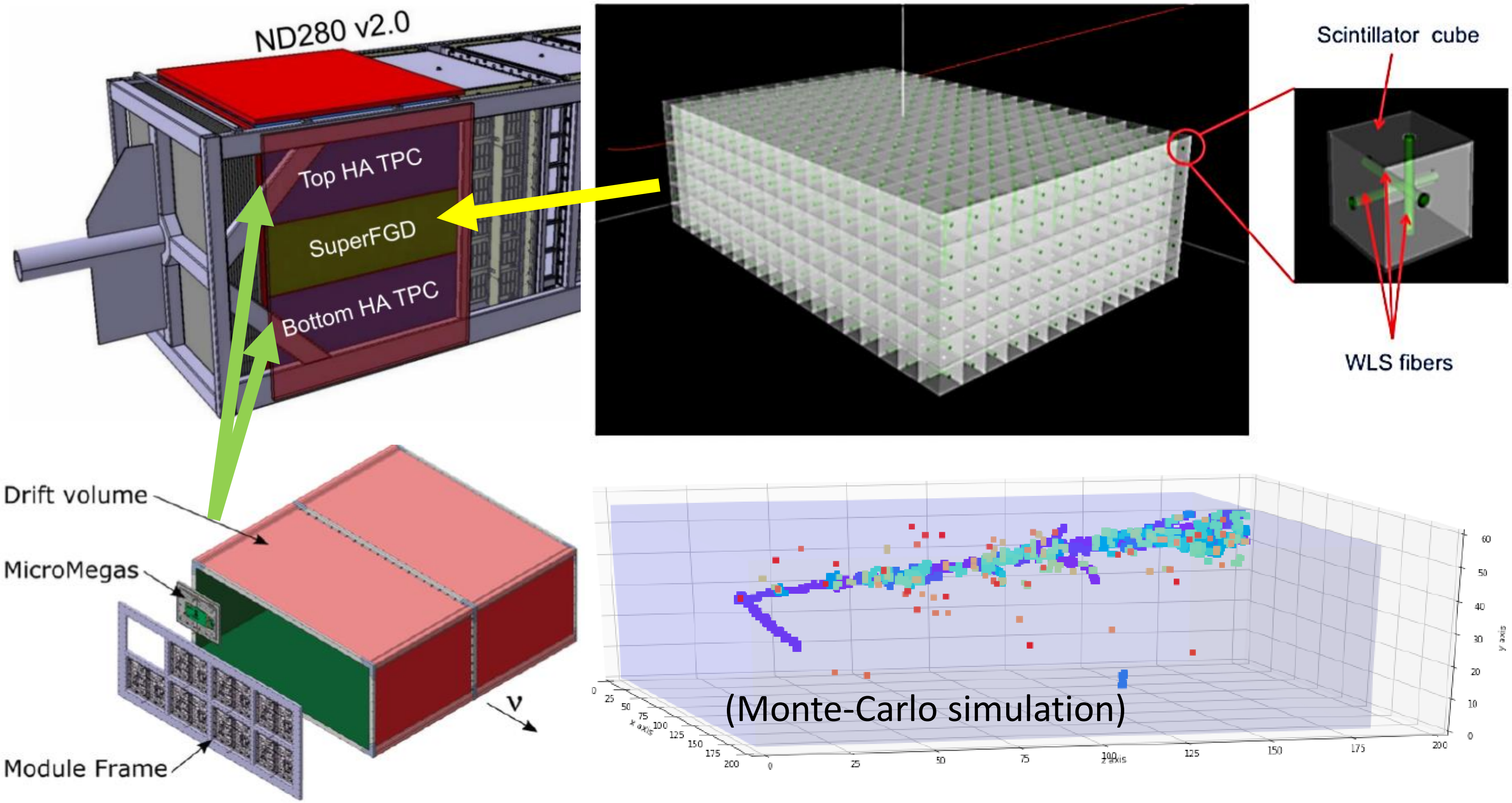


# of backward pions (low momentum) MC prediction is smaller than data.



New experiment (ND280 upgrade @ J-PARC, T2K)

- Realize higher resolution with scintillator and TPC with ToF.
  - Use scintillator cube (1cm x 1cm x 1cm)
  - Readout each cube using three fibers.



Summary

- Current and future neutrino oscillation experiments uses the nuclear target to measure neutrinos.

- "Uncertainty from the neutrino-nucleus interaction" is one of the major sources of the systematic error in the recent neutrino oscillation experiment.

- Low q^2 interactions are most difficult but have significant impact. Large q^2 interactions show non-negligible discrepancies but the statistics is rather small.

- Nuclear physics plays important role.
  Precise measurements of neutrino interactions.
  External inputs from electron or hadron scattering experiments and precise theoretical models are also essential.

fin.