Experimental neutrino cross sections (**a few hundreds of MeV ~ GeV**)

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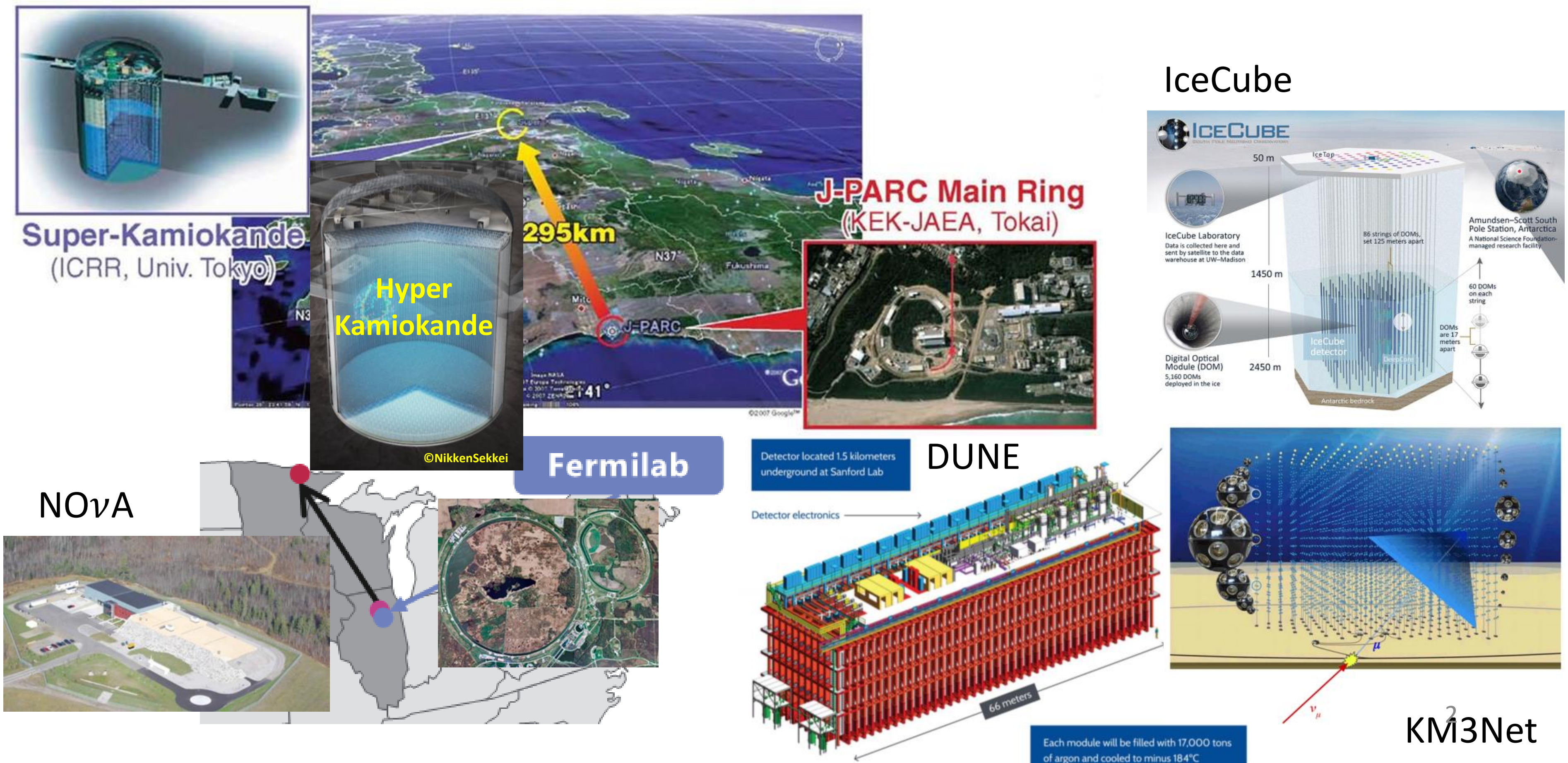
Recent and future accelerator and atmospheric neutrino long baseline neutrino oscillation experiments

Super-Kamiokande, IceCube, Km3Net, T2K, Hyper-Kamiokande (H_2O)
MiniBooNE, NOνA, JUNO (Scintillator), MicroBooNE, DUNE (Argon)

All experiments use nucleus as target.



Why do neutrino cross-sections (interactions) matter?

Available neutrino beams are not monochrome.

Atmospheric ν 100 MeV ~ TeV

Wide energy range

Wide travel distance (baseline)

All flavors ($\nu_e, \overline{\nu_e}, \nu_\mu, \overline{\nu_\mu}$)

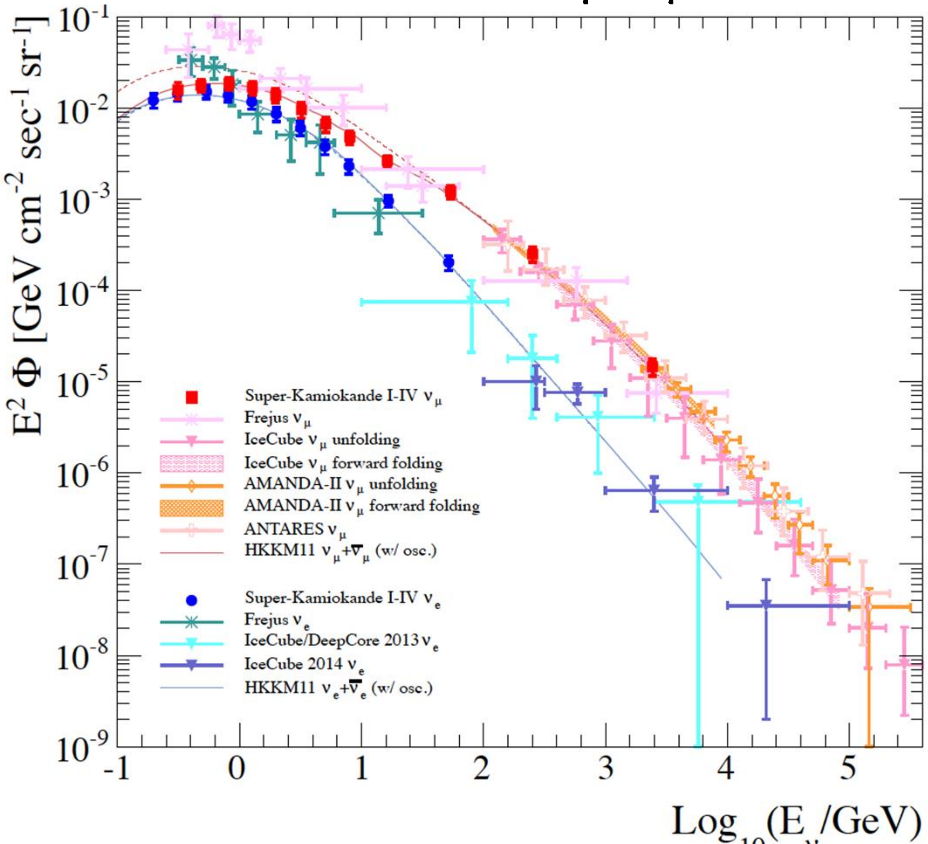
Accelerator ν 100 MeV ~ 10 GeV

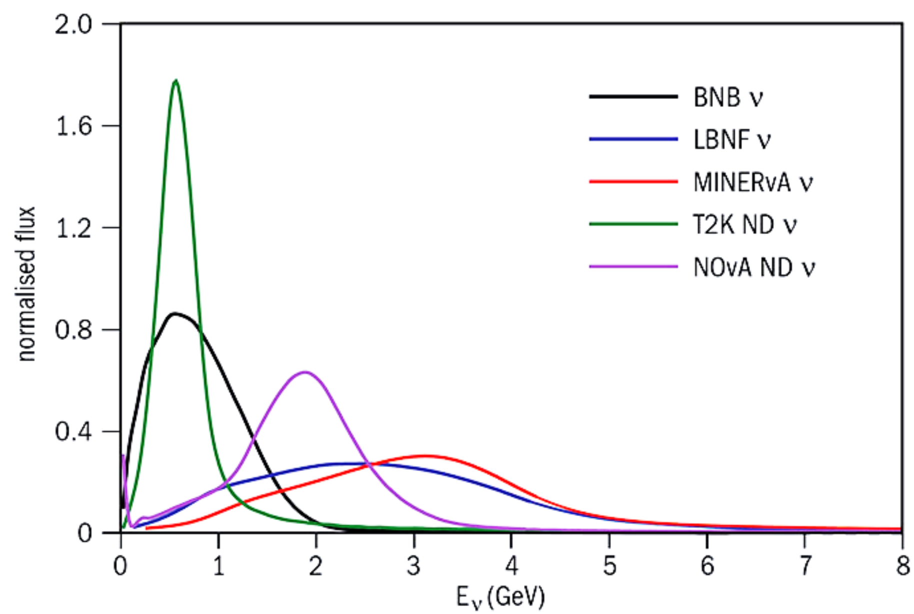
Narrower energy range

Fixed travel distance (baseline)

Mostly ($\nu_\mu, \overline{\nu_\mu}$) in the beam

(Small fraction of ν_e and $\overline{\nu_e}$)





Why do neutrino cross-sections (interactions) matter?

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

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

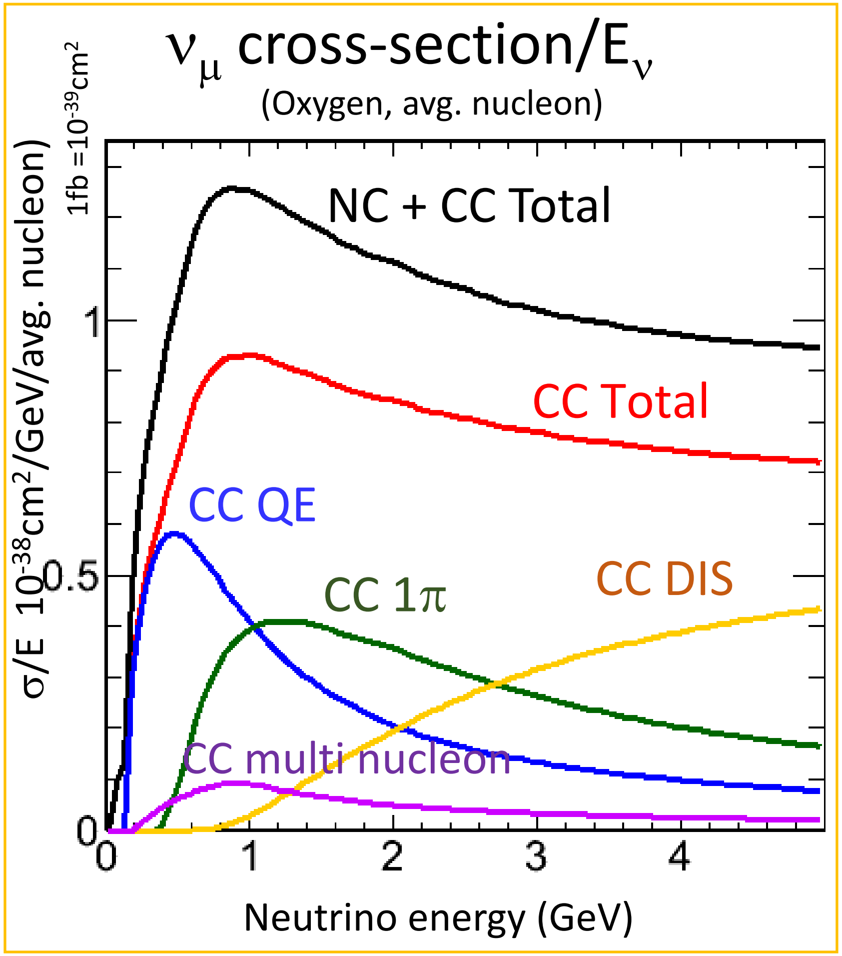
(radiative decay of resonance)

Deep inelastic scattering

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

Coherent Single meson productions

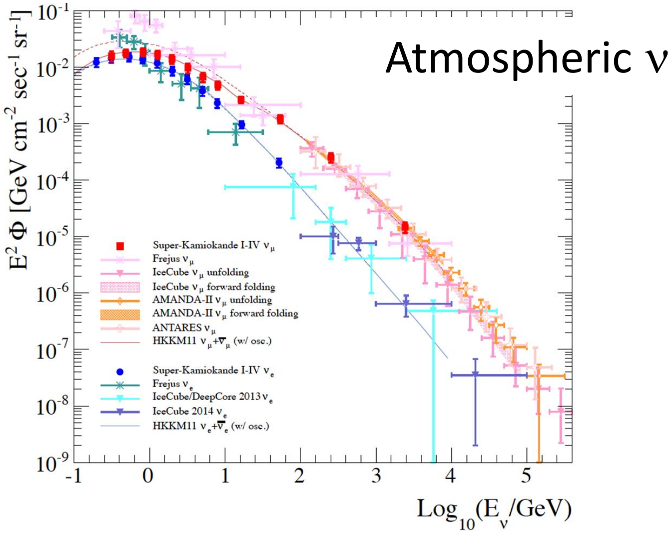
$$\nu + A \rightarrow l^-(\nu) + A' + \pi^+(\pi^0)$$

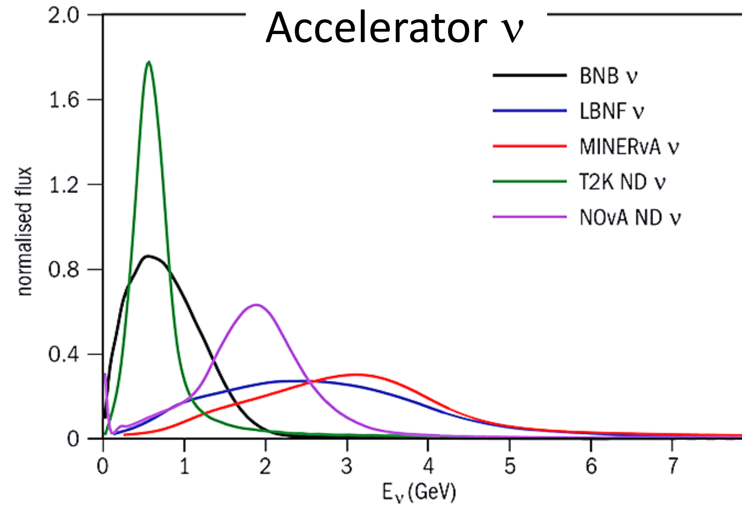


Neutrino detectors ~ nucleus target

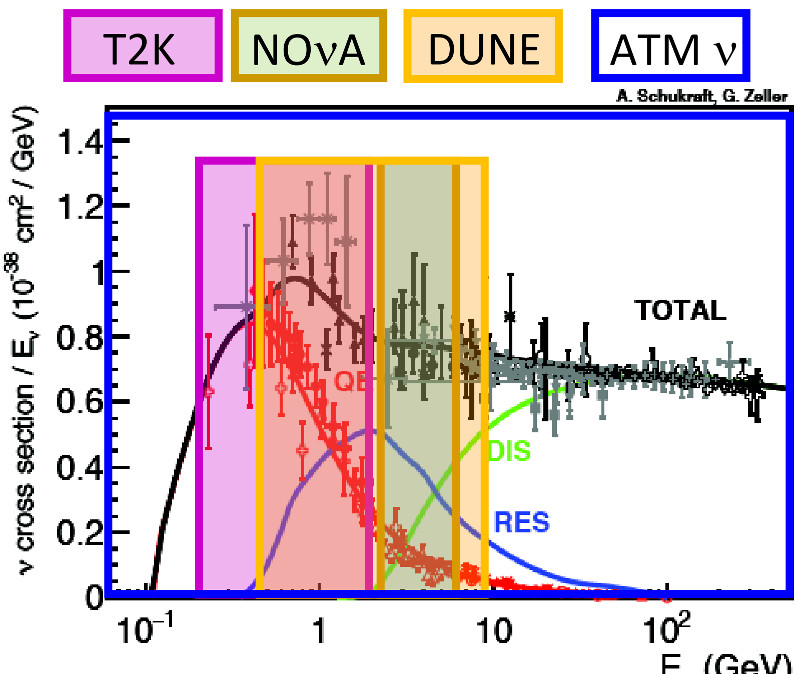
Various "nuclear effects" have to be taken into account.

Neutrino flux and neutrino interactions

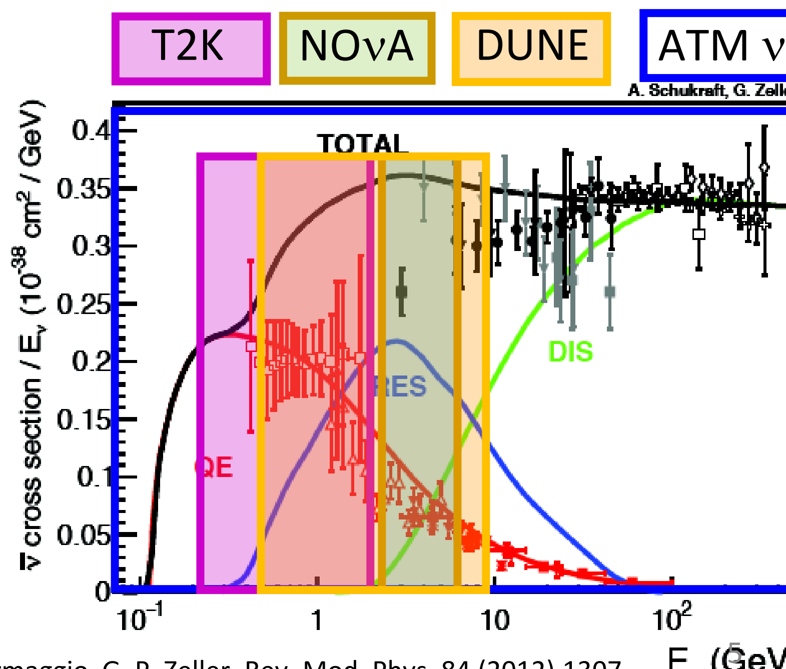




Neutrino cross-section



Anti-neutrino cross-section

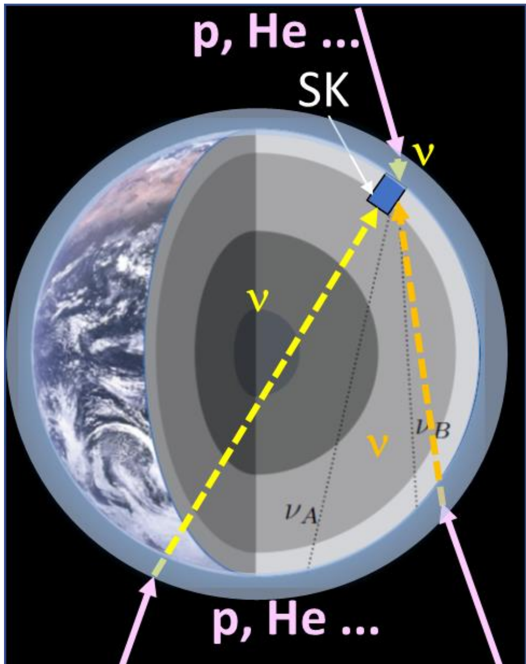


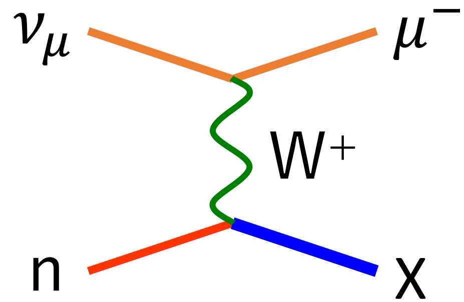
J. A. Formaggio, G. P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

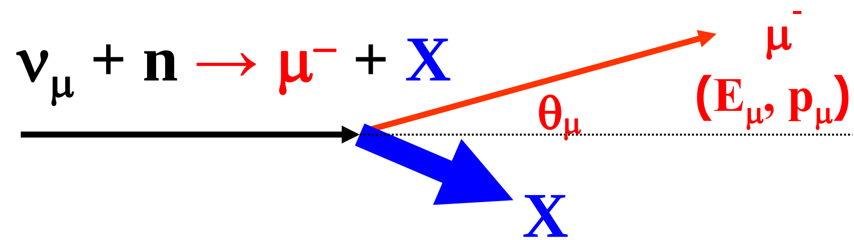
Methodology of neutrino oscillation experiments

Case 1: Atmospheric neutrinos, E_ν > 100MeV

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



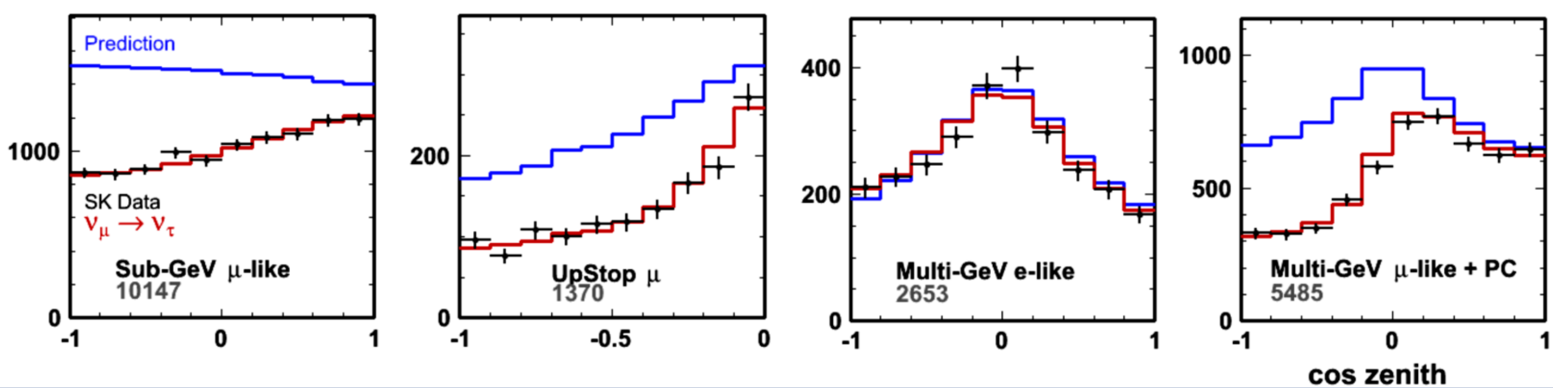




Compare the observed lepton momentum and directions with the "expected" distributions with various oscillation parameters.

(few exceptions)

Zenith angle distribution of various samples



Methodology of neutrino oscillation experiments

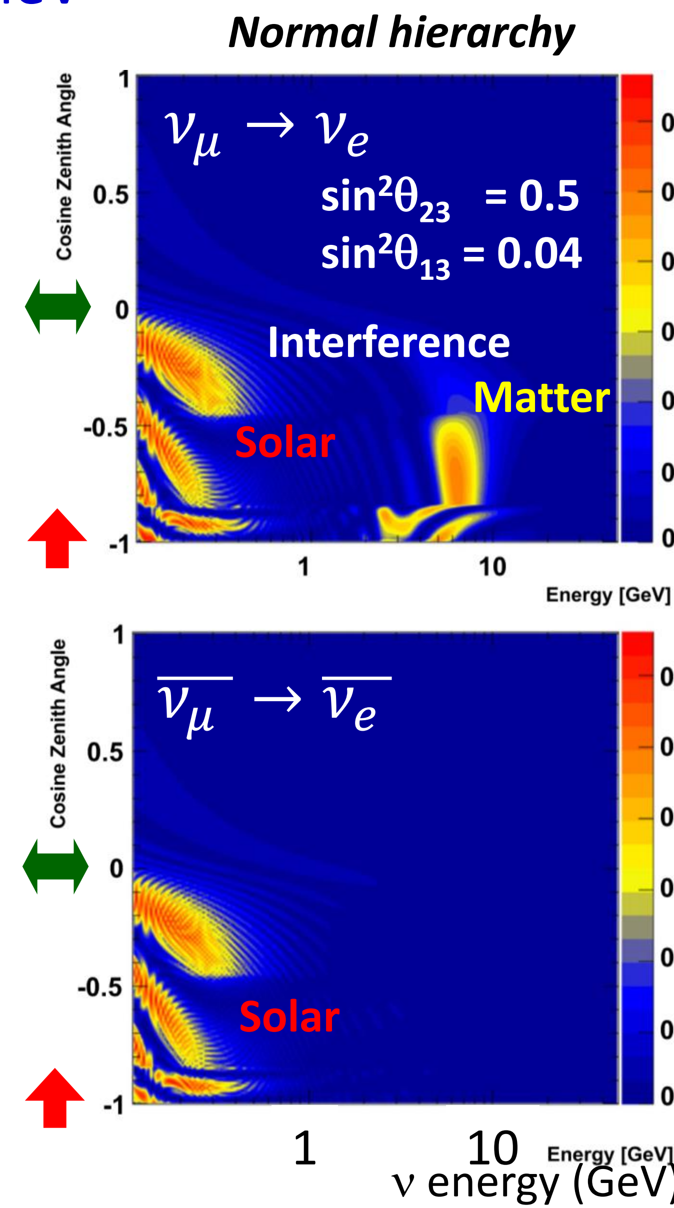
Case 1: Atmospheric neutrinos, E_ν > 100MeV

Different appearance probabilities of ν_e and $\overline{\nu_e}$

Difference in # of electron events:

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

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



- Matter effect ~ from mass hierarchy
  Possible enhancement in several GeV
  passed through the earth core
  One of the flavors (ν_e or $\overline{\nu_e}$) shows this enhancement.
- Solar term from θ_{23} octant degeneracy
  Possible ν_e enhancement in sub-GeV
- Interference CP phase

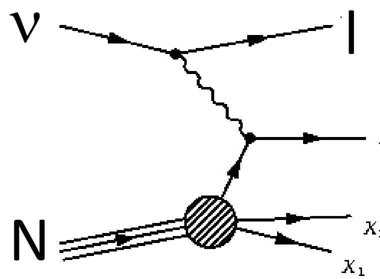
Methodology of neutrino oscillation experiments

Case 1: Atmospheric neutrinos, E_ν > 100MeV

Statistically separate ν_e and $\overline{\nu_e}$

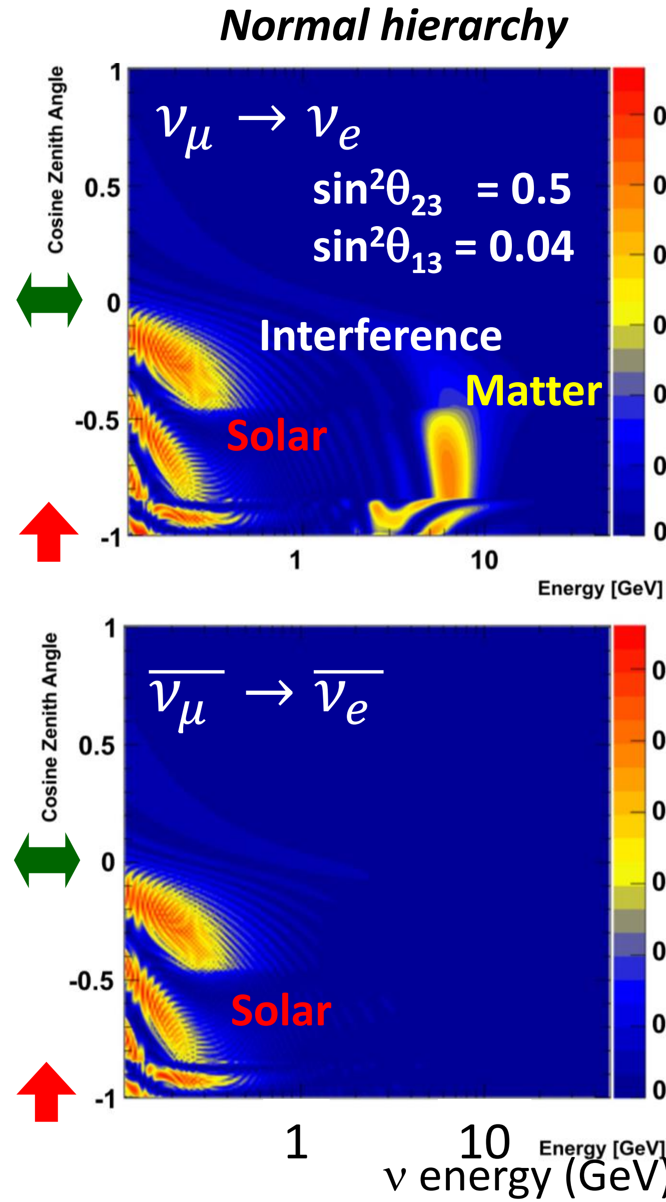
Dominant interaction (a few ~ 10 GeV)

→ Deep inelastic scattering

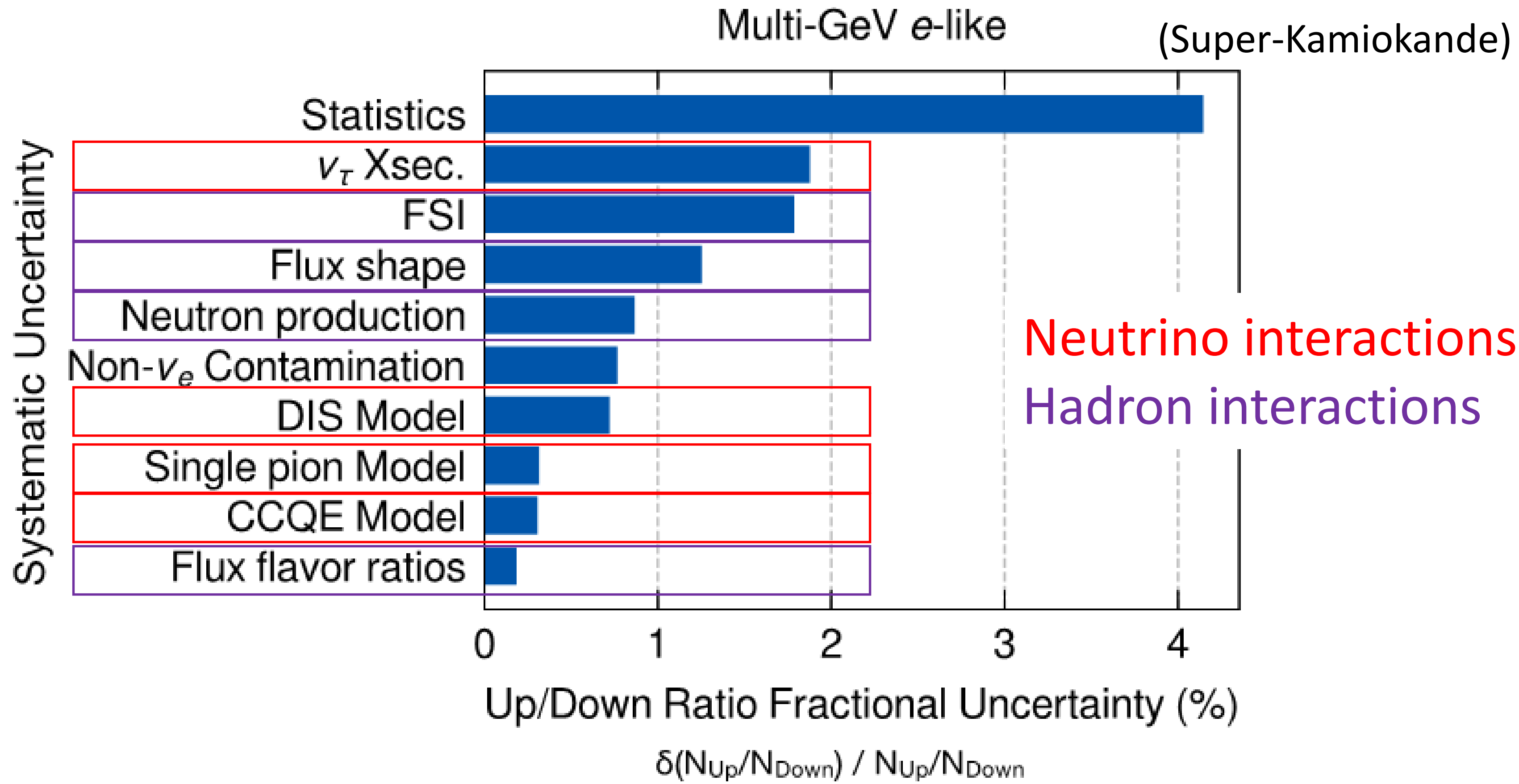


Differential cross-sections are different

Observables	ν_e *CC*	$\overline{\nu_e}$ *CC*
Number of rings	More	Fewer
Transverse momentum ratio	Larger	Smaller
E Fraction of energetic ring	Smaller	Larger
# of decay electrons	More	Fewer
# of neutrons	Fewer	More



Systematic uncertainties (Atmospheric neutrino @ SK)

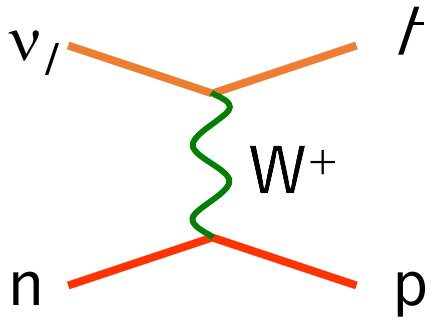


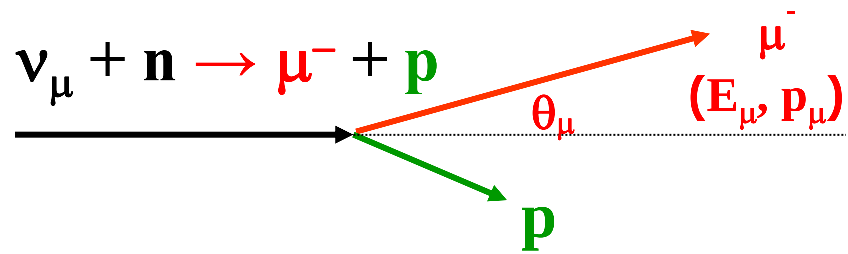
- Downward-going neutrinos constrain many flux and cross-section uncertainties.
- Systematic uncertainties with asymmetric zenith angle dependence have the largest effect on mass ordering analysis.
- However, this analysis is statistically limited.

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



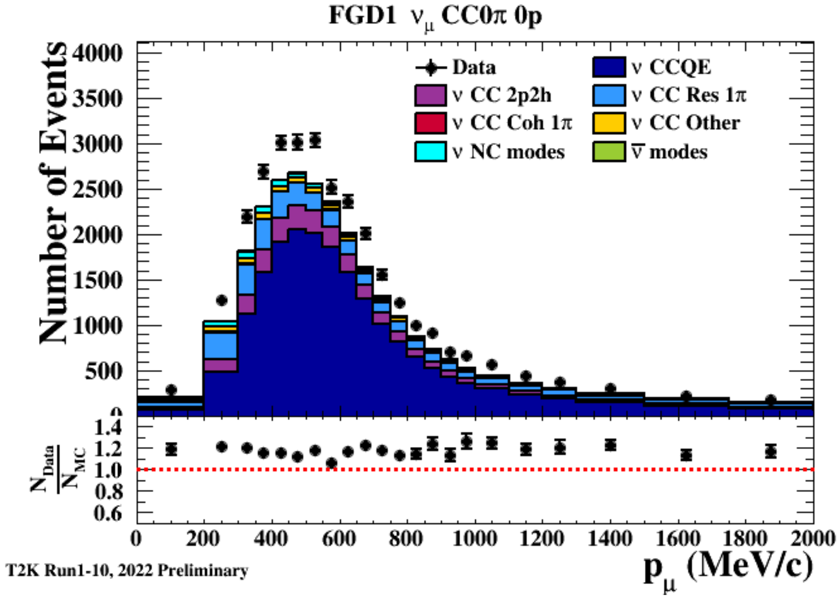


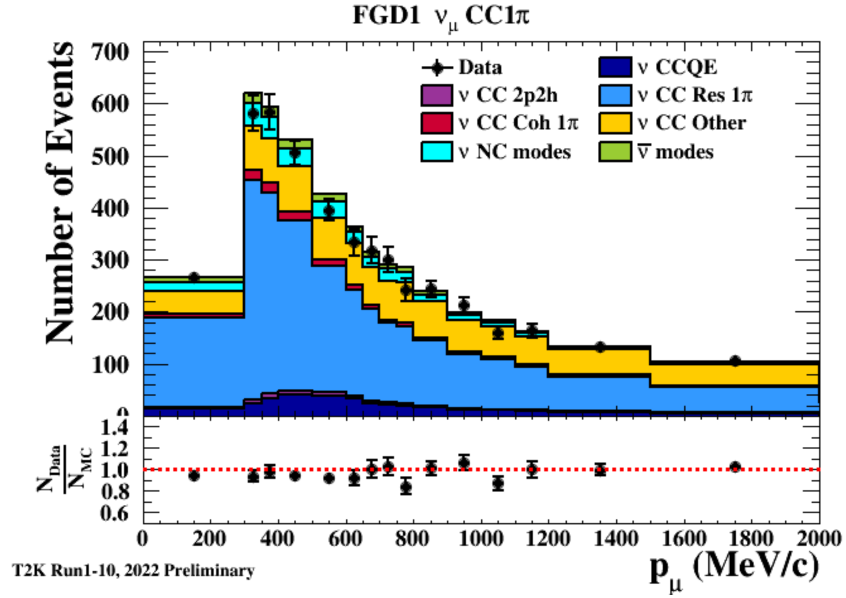
Accelerator based experiment → Known neutrino direction

Use **direction and momentum of lepton** to reconstruct (estimate) energy of neutrino but experiments use “nucleus“ target.

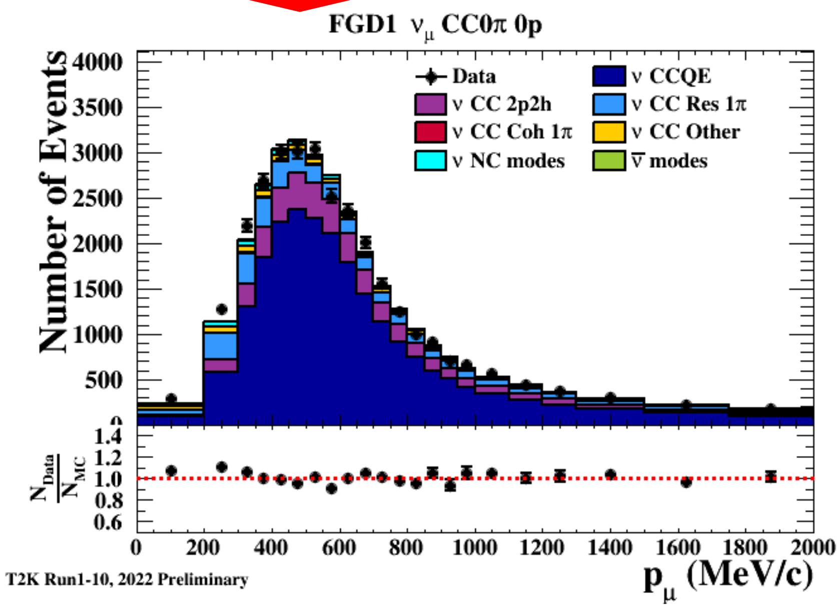
- Purity of the selected events
- Binding effects of target nucleus
  Fermi momentum, Binding energy etc.
- Contamination ~ Impurity
  Interactions other than genuine CCQE, like multi-nucleon interaction.

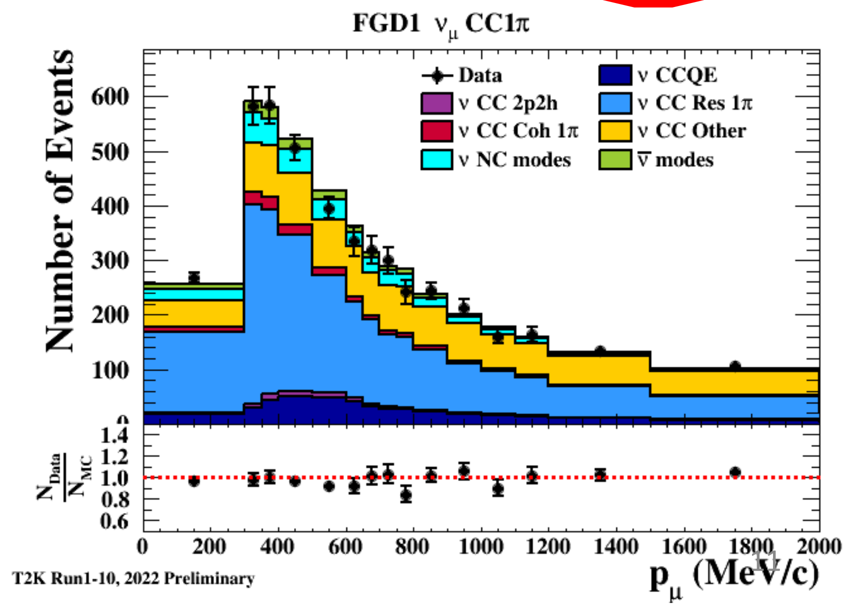
T2K ~ Constraints from near detector measurements





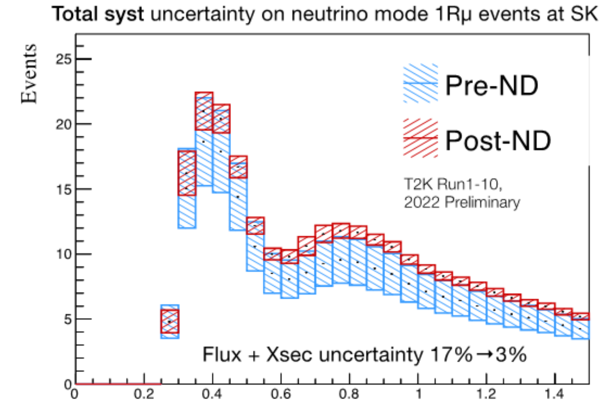
Flux & neutrino interaction parameter fitting





Systematic uncertainties (T2K experiment)

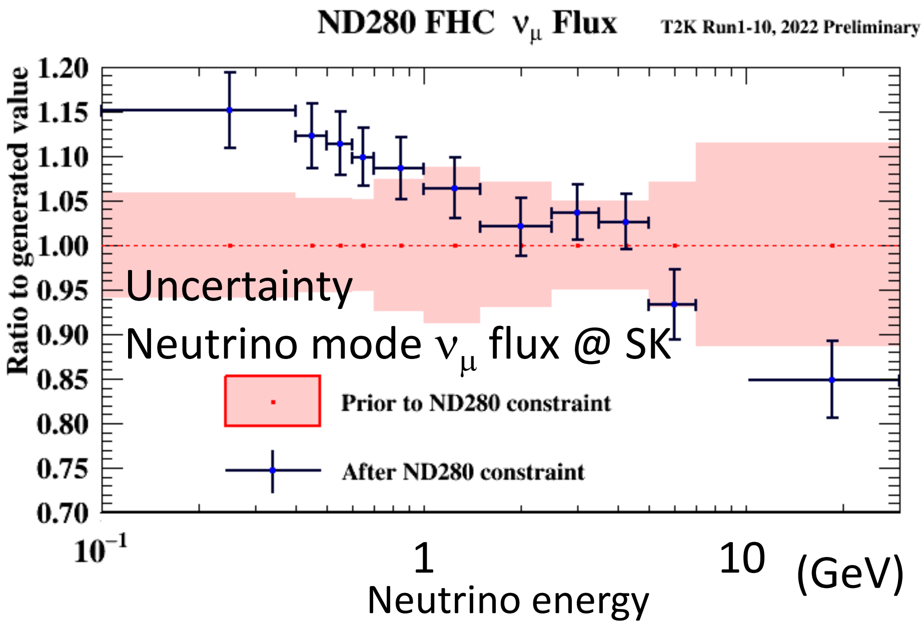
Near detector measurements reduce the systematic uncertainty drastically, from 17% to 3%

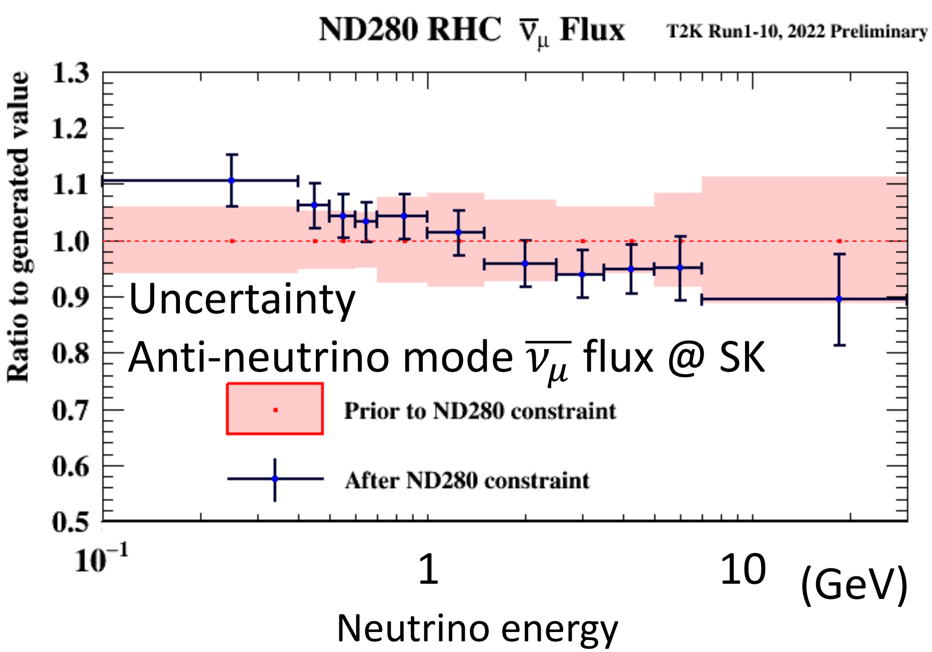


Before fitting

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6
After fitting							
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

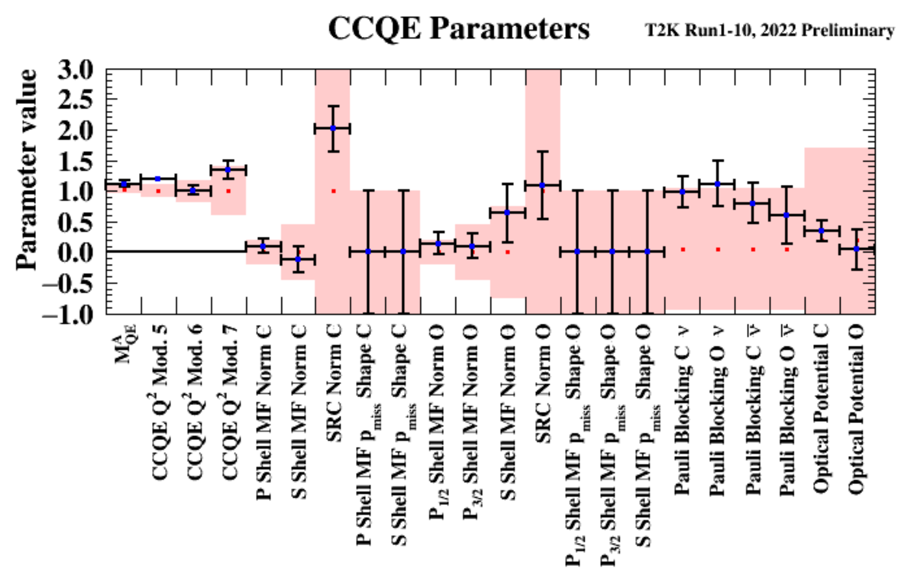
T2K ~ Constraints from near detector measurements





Fit neutrino energy spectrum and neutrino interaction model parameters simultaneously.

Some of the neutrino interaction model parameters



*) Pre-fit central values & errors are estimated with external data

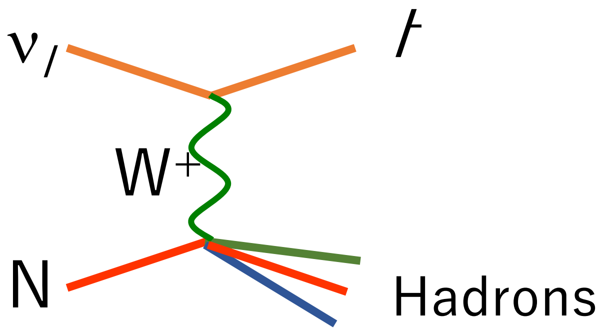
Methodology of neutrino oscillation experiments

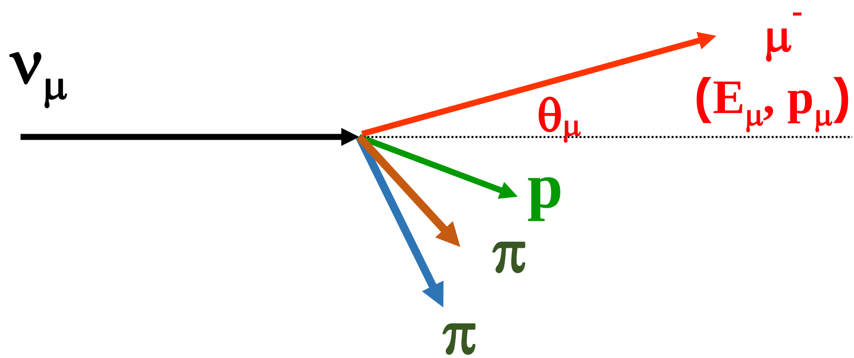
Case 3: Accelerator neutrinos, E_ν > several GeV

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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mainly **ν + N → *l* + N' + hadrons**

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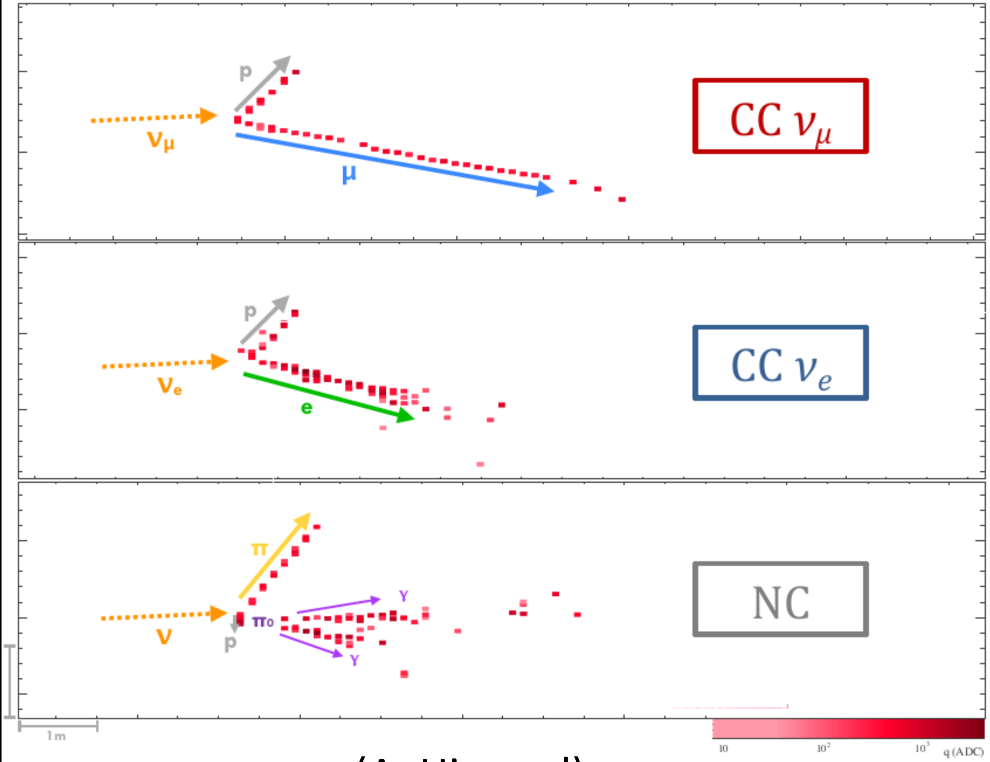
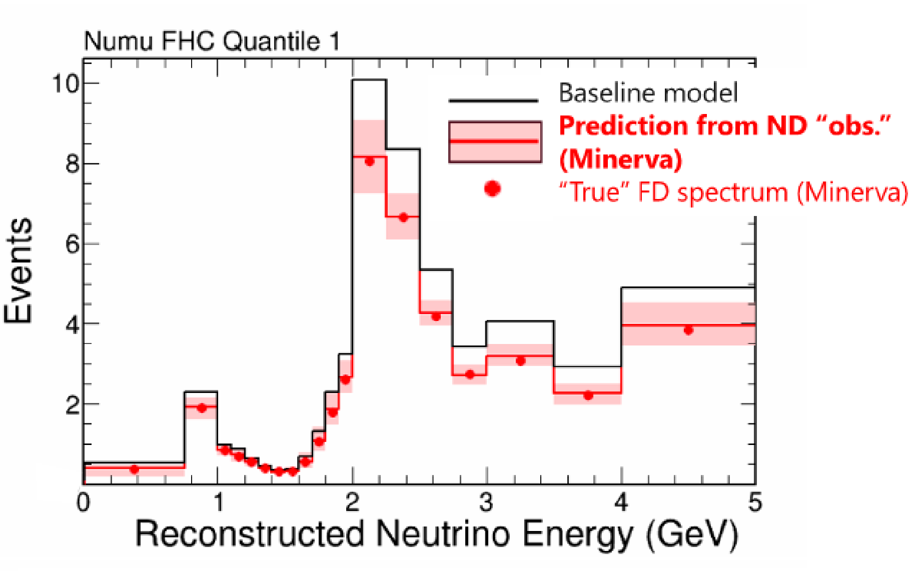
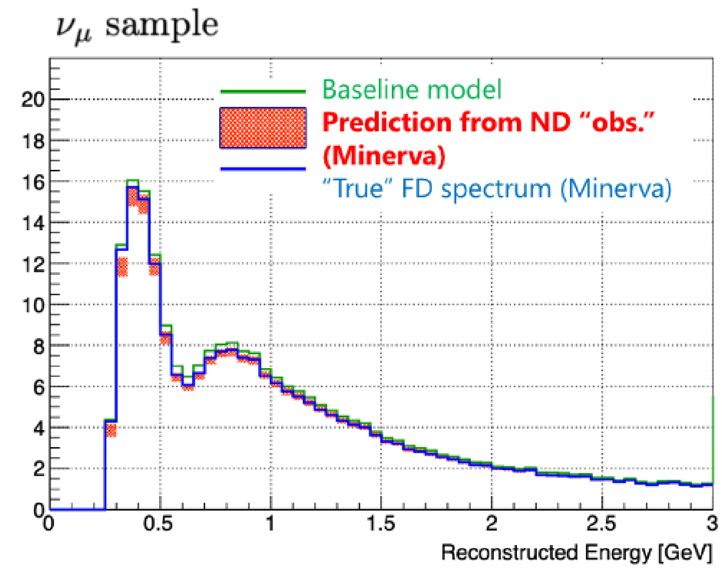


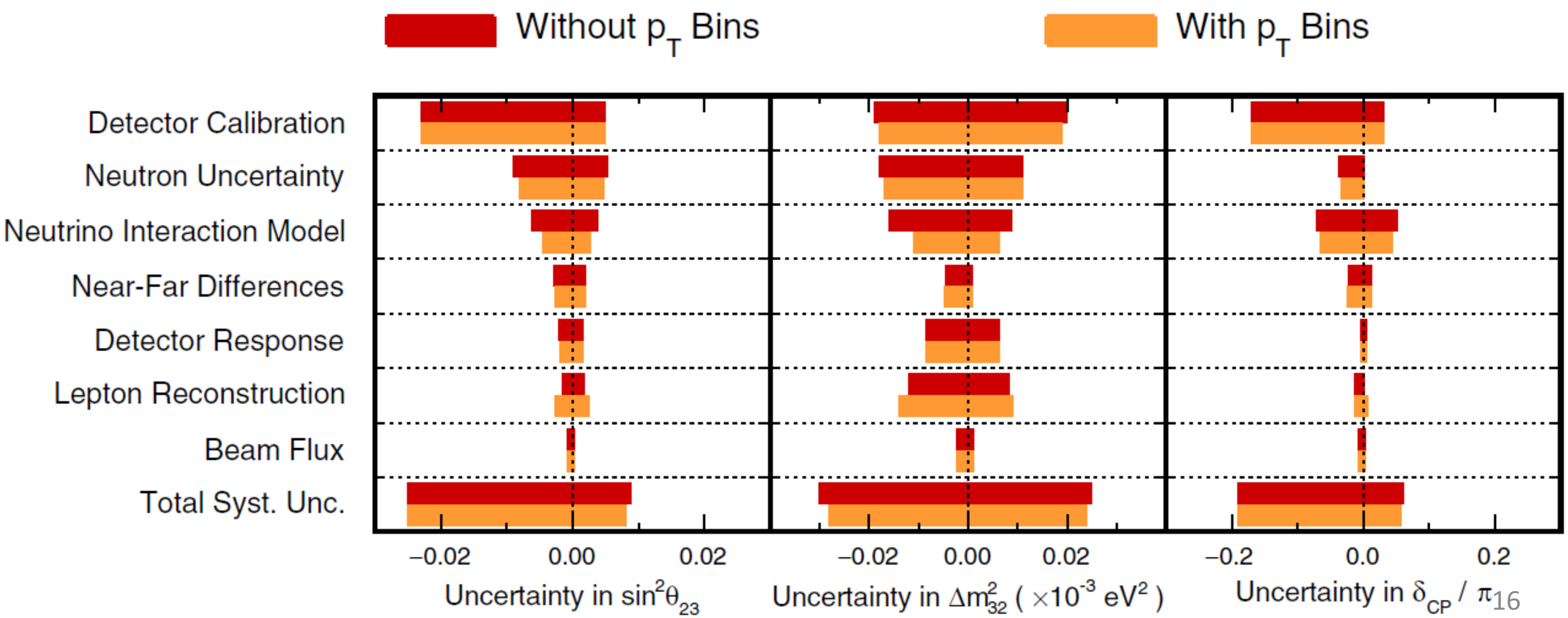
(A. Himmel)

- 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.

Systematic uncertainties (NOνA experiment)







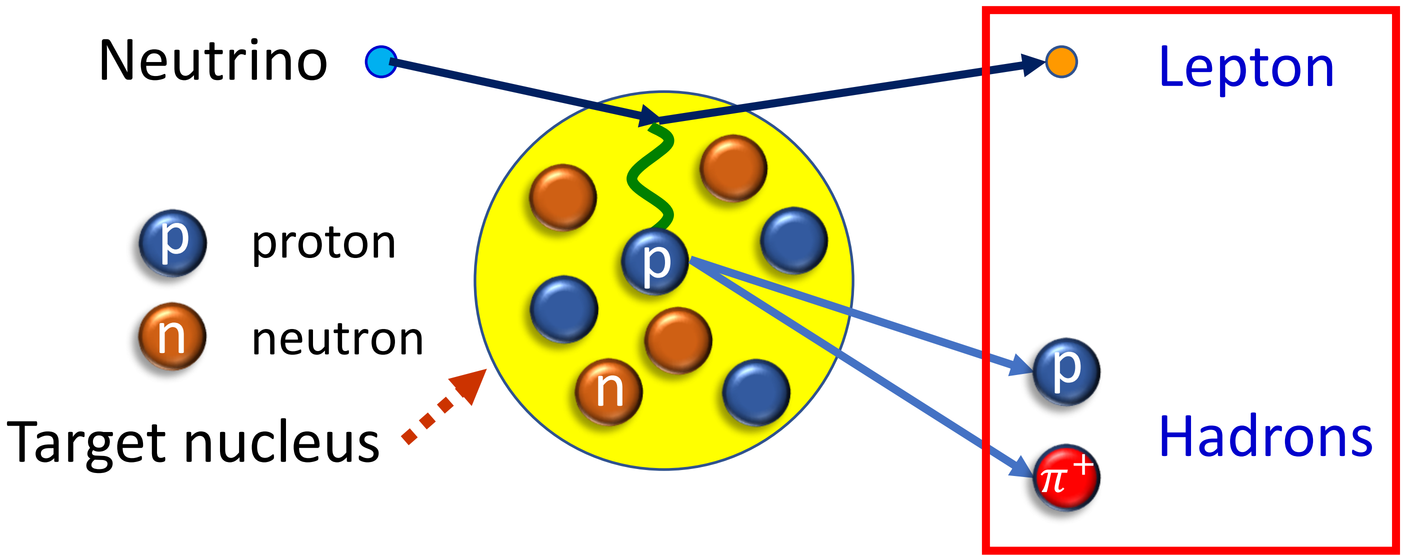
How we study neutrino interactions

We can not observe or measure neutrinos” directly.

We must “reconstruct” neutrino information from observed particles, unless we just count the number of neutrinos.

Example (1 pion production)

$$\nu\, p \rightarrow l^{-}\, p\, \pi^{+}$$



Use particle ID information and measured kinematic distributions of “observed” lepton and hadrons to identify neutrino flavor and reconstruct energy and direction.

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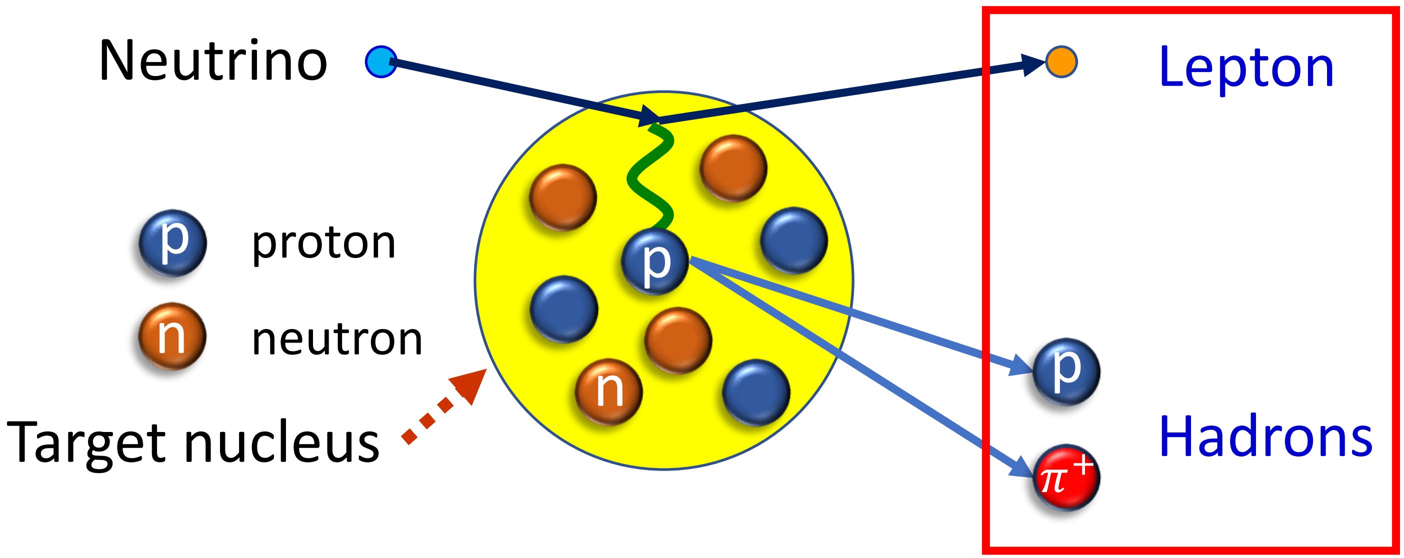

The "real" detectors can not detect or measure all the particles.

Momentum threshold (or acceptance) and resolution, angular acceptance, particle identification, charge separation etc…

How we study neutrino interactions

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We must “reconstruct” neutrino information from observed particles, unless we just count the number of neutrinos.

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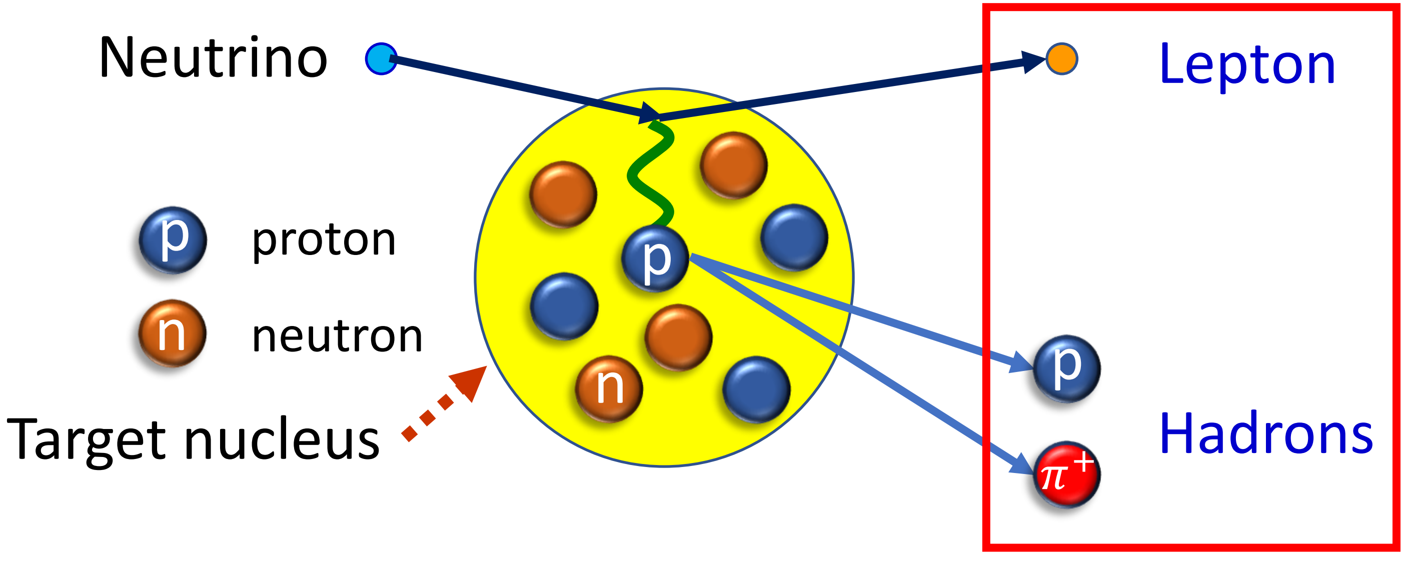


Neutrino information needs to be “reconstructed” using our knowledge of neutrino-nucleon/nucleus interactions.

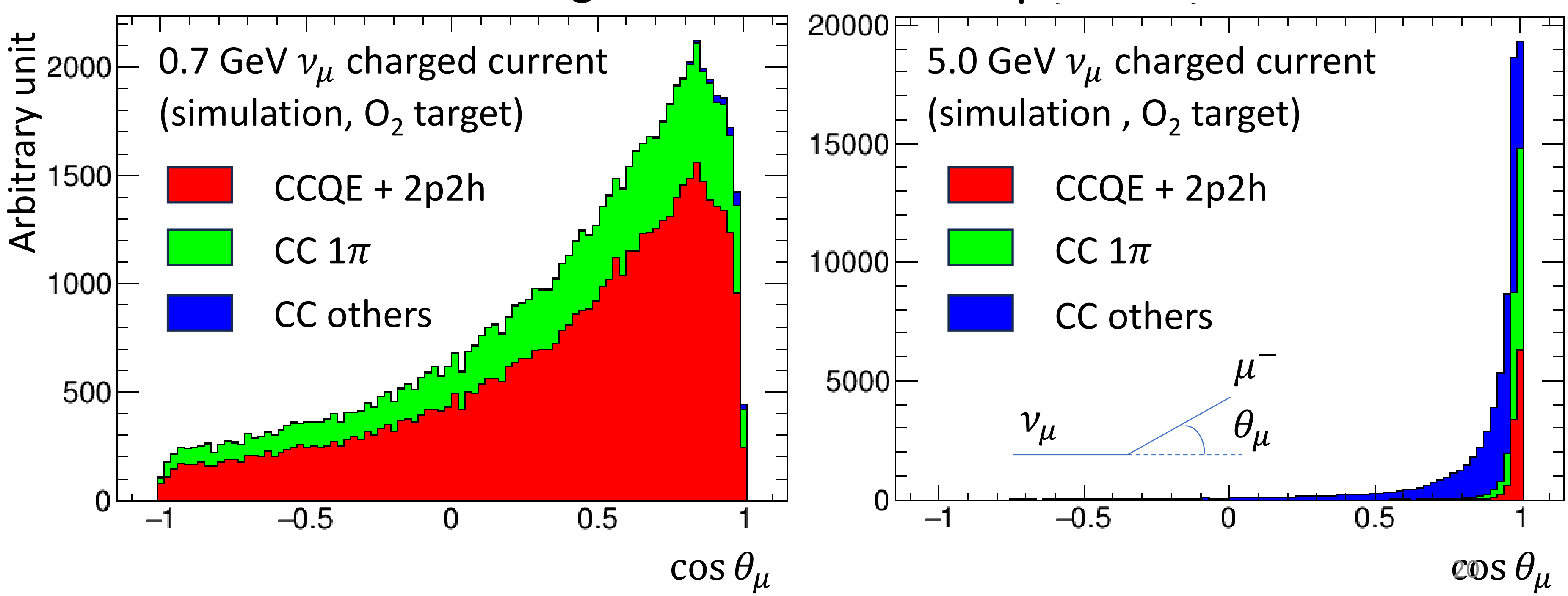
Understanding of neutrino interactions

How we study neutrino interactions

Requirements for the neutrino detectors are significantly different depending on the energy of neutrinos.

1. Interactions are quite different.
2. Directional distribution of outgoing leptons are quite different.
3. Number of generated particles are quite different.

Angular distribution of μ^-



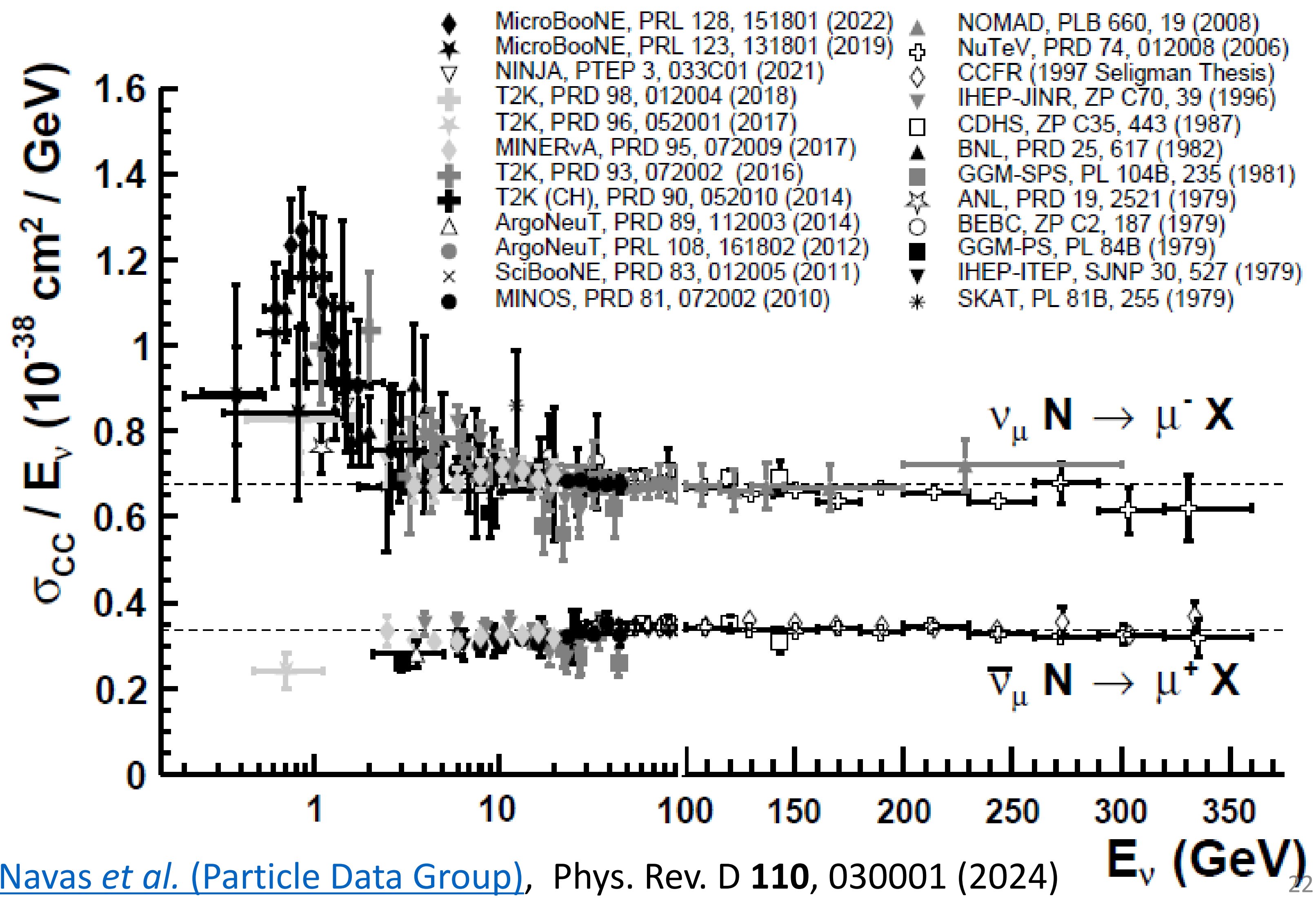
Current issues in understanding/measuring neutrino-nucleon/nucleus cross-sections

1. Neutrino energy is not monochromatic, and neutrino flux (absolute rate and shape) predictions have uncertainties.
2. Neutrino energy needs to be reconstructed using the observed particles in the detector. However, not all the particles are visible in the detector.
3. Recent detectors use nucleus target, and neutrino-nucleon and neutrino-nucleus interactions have large uncertainties.
   1. Various interaction channels exist.
      $\nu N \rightarrow l^- N', \nu N \rightarrow l^- \pi N', \nu N \rightarrow l^- N' + hadrons, etc.$
   2. Neutrino nucleon interactions need various experimental inputs. Some of them requires neutrino experiments. (Axial-vector part)
   3. Nuclear (binding) effect affects significantly.
4. Produced hadron interactions in and out of the nucleus have uncertainties.

Current status of “neutrino cross-section” measurements

Inclusive charged current total cross-section

G.P. Zeller (PDG review 2024)

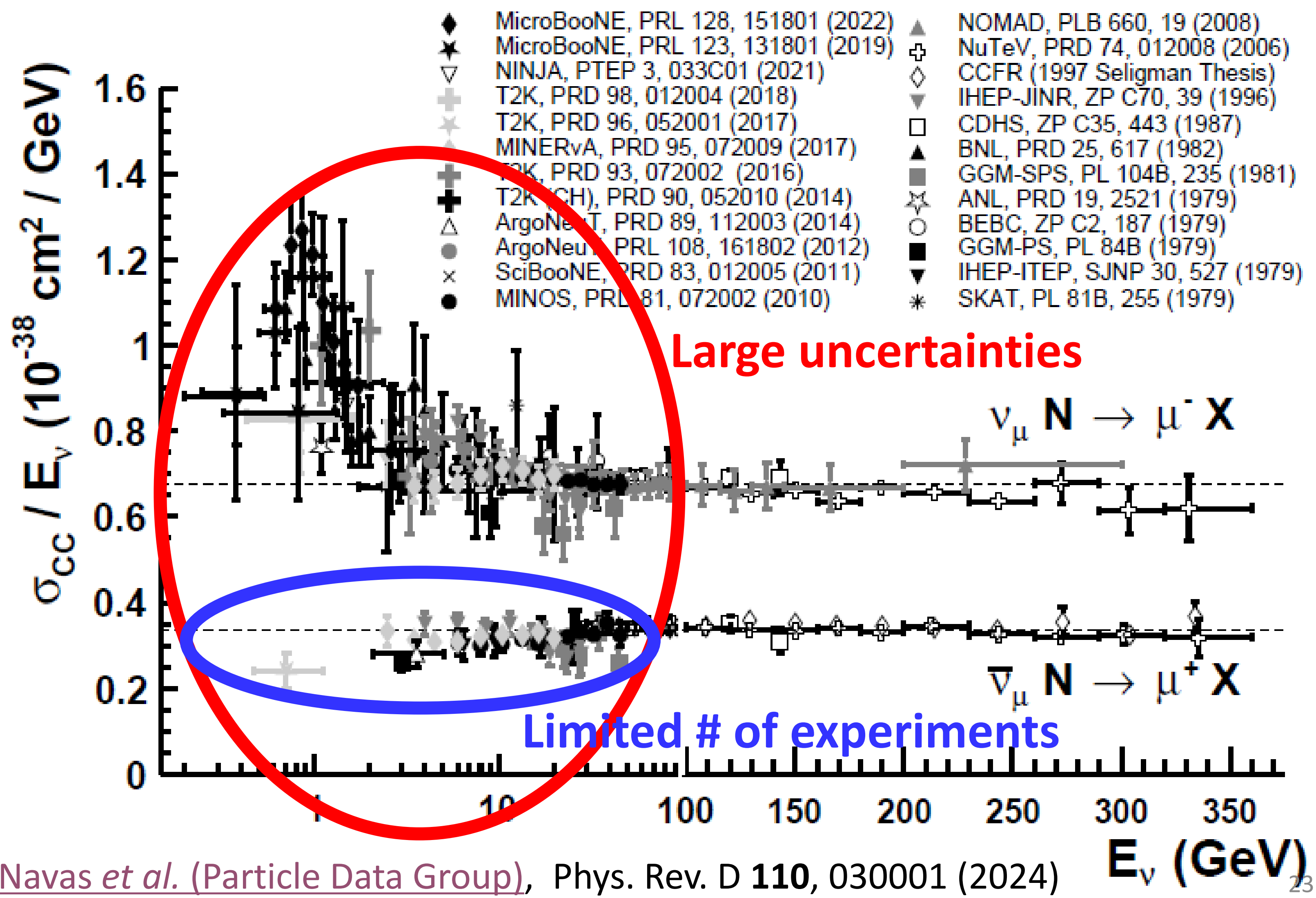


S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

Current status of "neutrino cross-section" measurements

Inclusive charged current total cross-section

(G.P. Zeller's review)



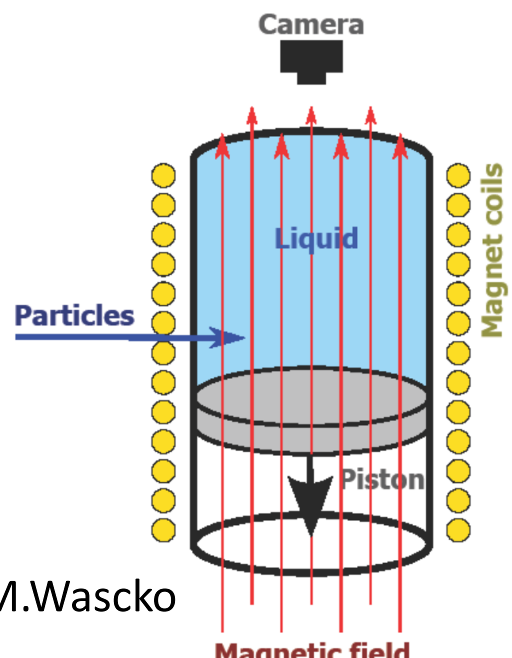
S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

Cross-section measurement

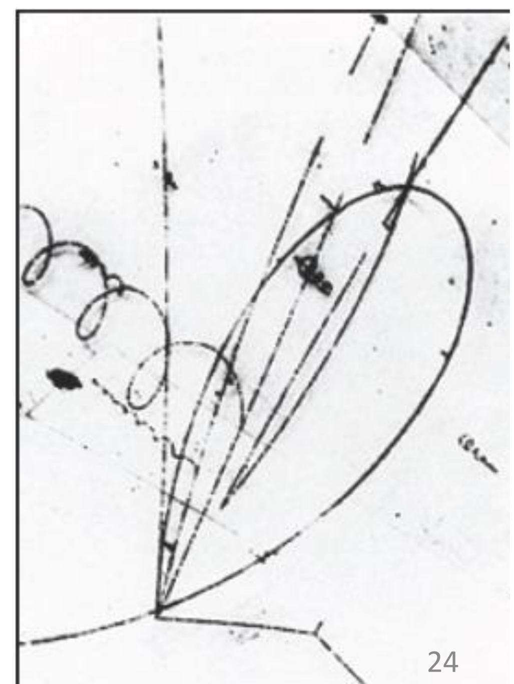
Bubble chamber

Extensively used in 1960s to 1980s.

- Super heated liquid as target. Initially D2, later Freon.
- Lower the pressure when the particle comes by pulling the piston.
- Generated charged particles ionize the liquid and create bubbles.
- Take pictures using a camera, find the trajectory (bubbles) in the image and reconstruct the tracks.



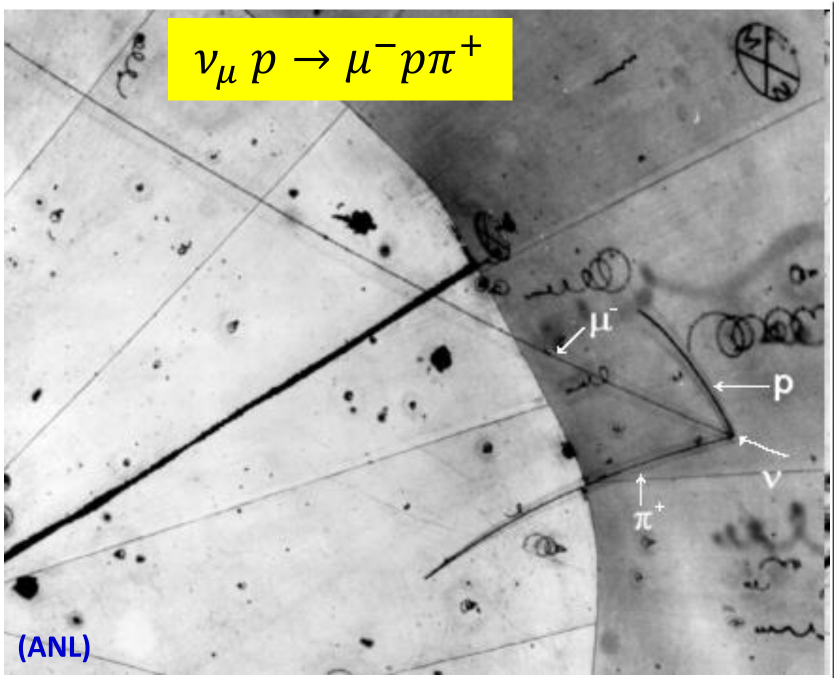
M.Wascko

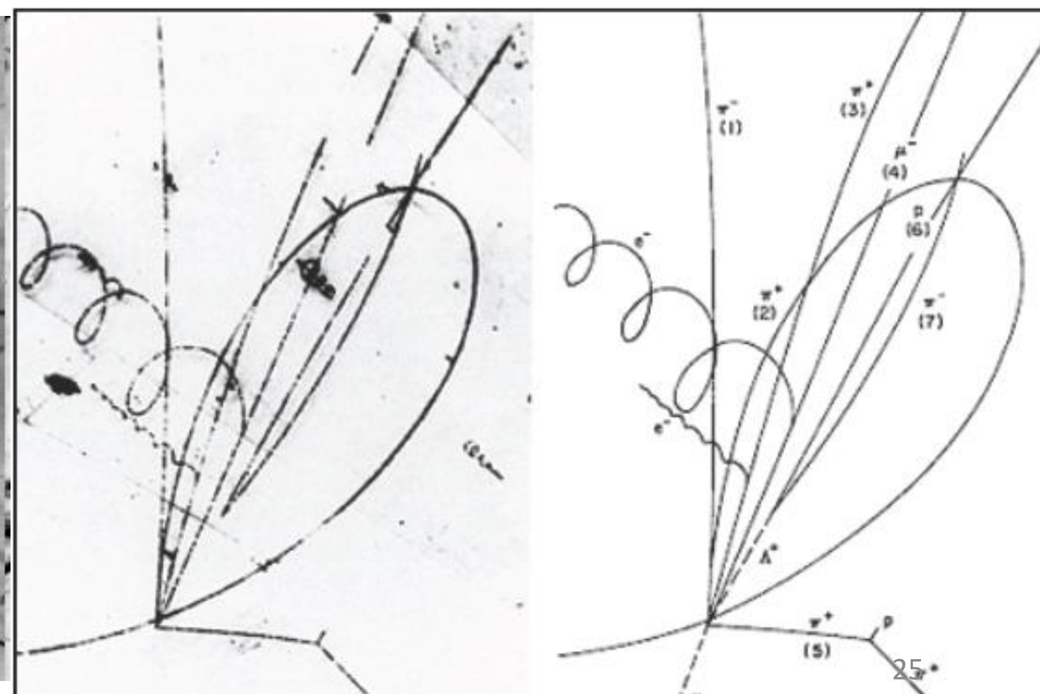


Cross-section measurement

Bubble chamber

- Curvature can be used to measure momentum and charge.
- Thickness of the track corresponds to the energy loss.
  -> Used to identify particles.
- High particle detection efficiency
  even for low momentum heavy particles, like protons.

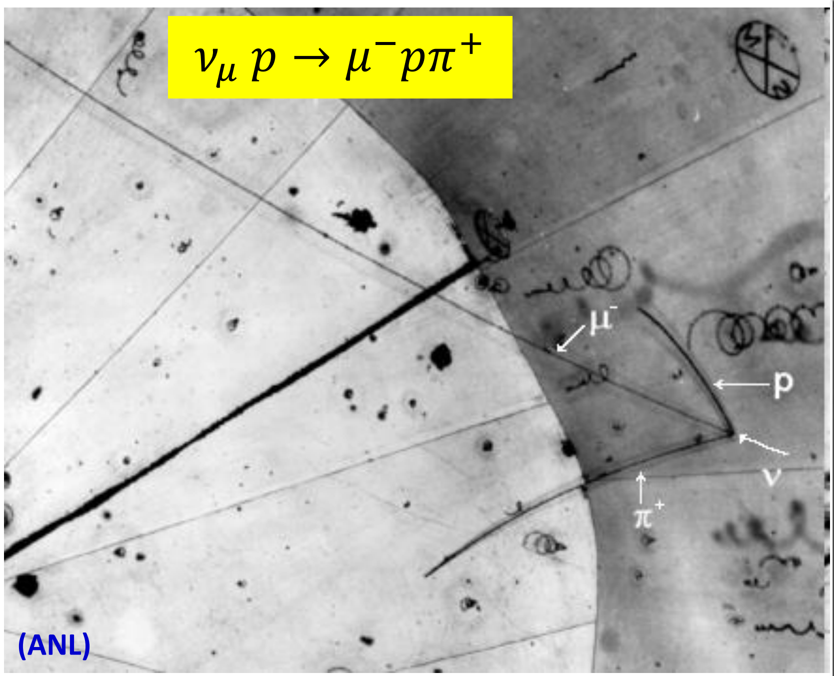


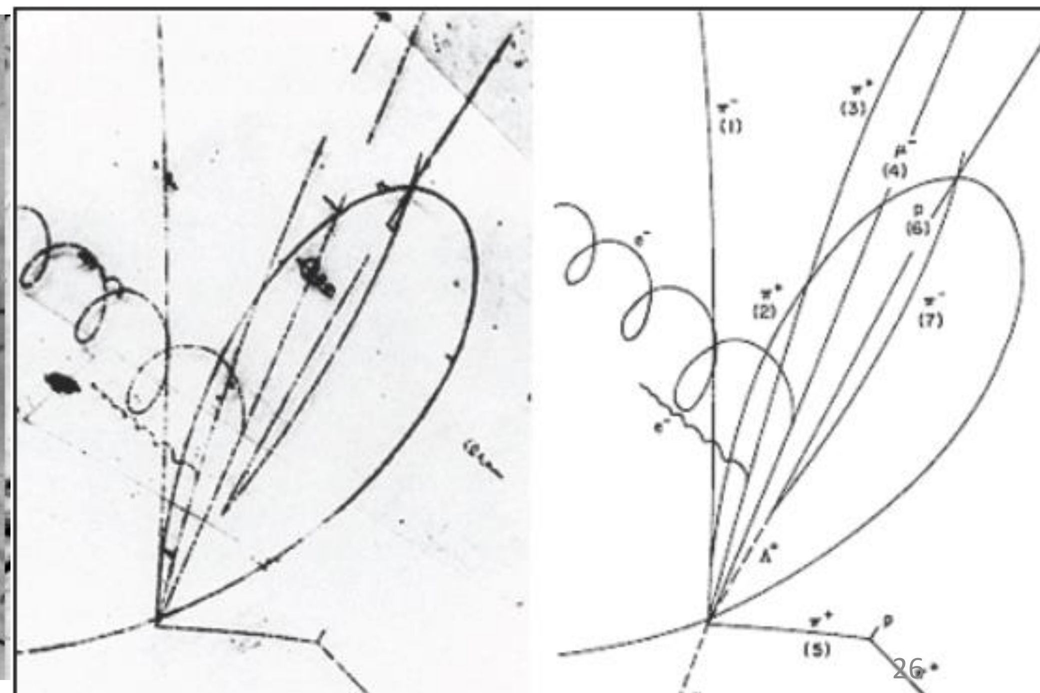


Cross-section measurement

Bubble chamber

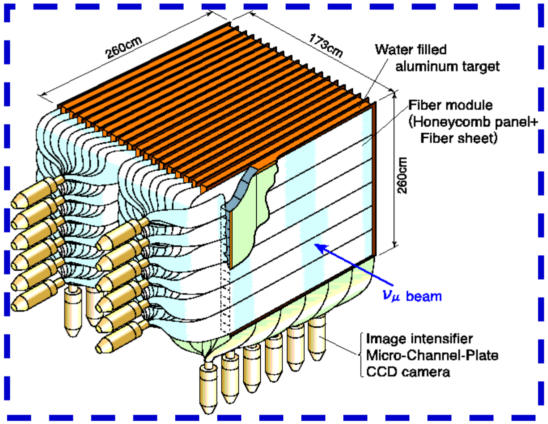
- Limited by statistics because of the detector mass and the scanning method (= by eye). At most a few thousands events.
- Separation of μ and charged π was rather difficult.
  It is difficult to differentiate particles with similar mass and same charge. (= Thickness of the track is similar.)
- π^0 detection efficiency was not high due to the limited volume.





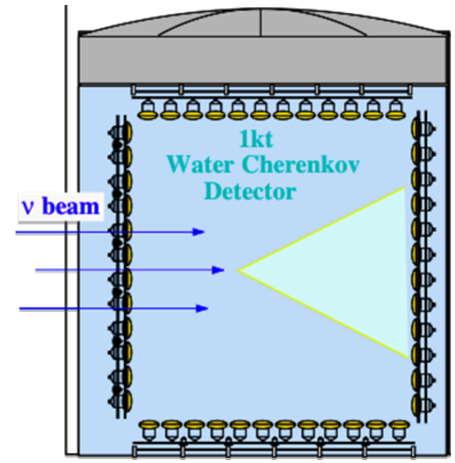
Cross-section measurements

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

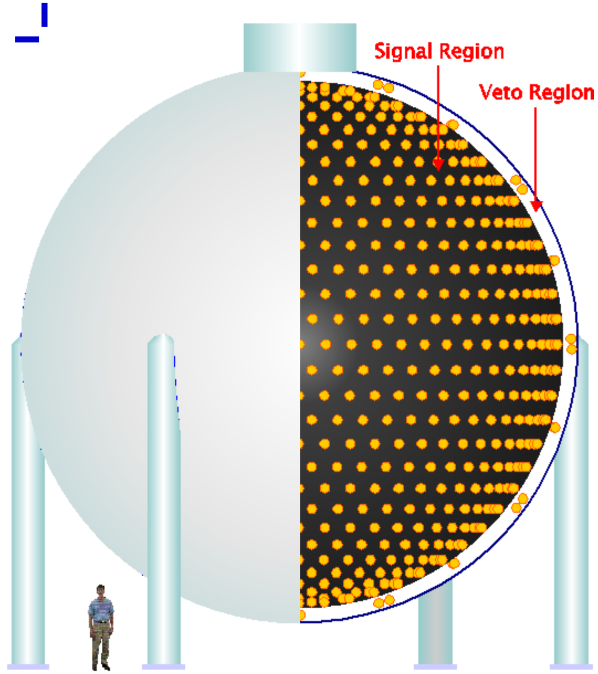


Scintillation fiber tracker with water container@K2K (SciFi @ KEK, K2K)

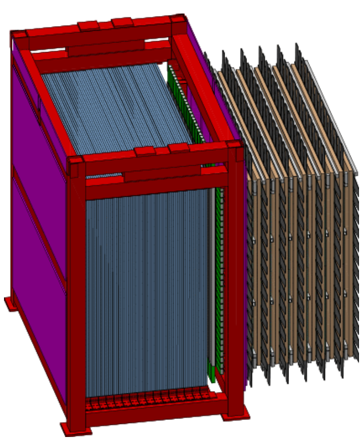
1kt Water Cherenkov detector (@ KEK, K2K)



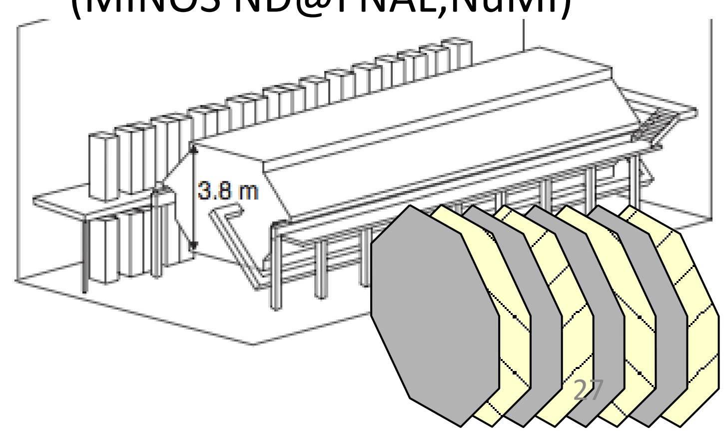
Oil Cherenkov detector (MiniBooNE@FNAL, BNB)



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



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

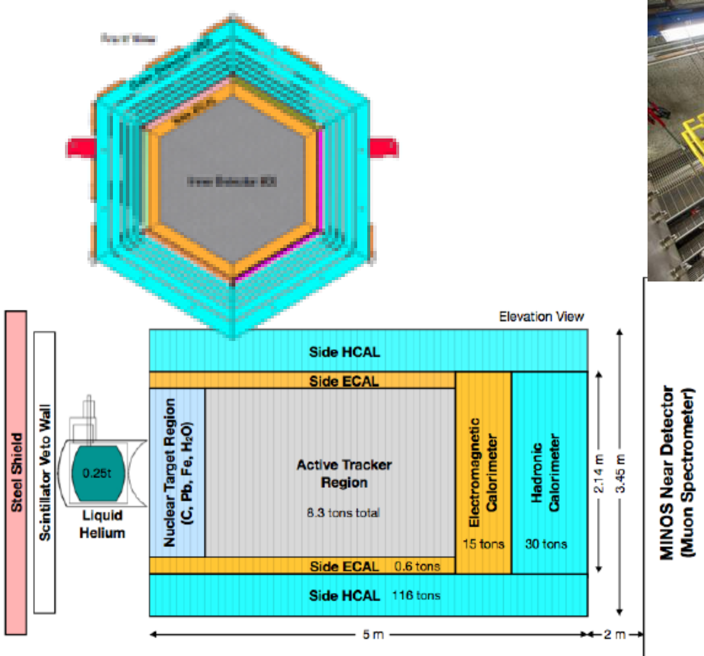


Cross-section measurements

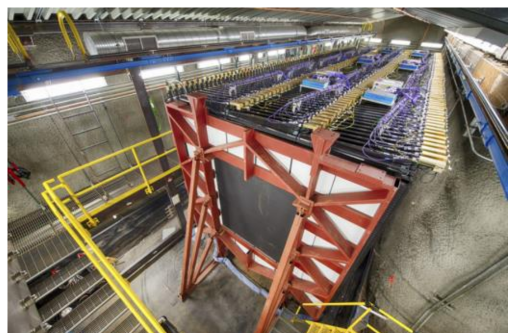
More recent experiments

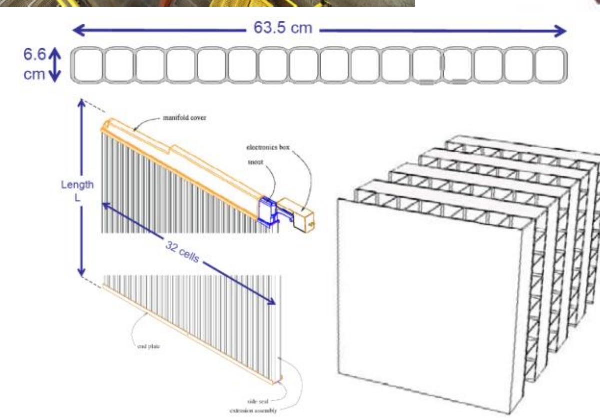
- High statistics (with intense neutrino beam)
- Low momentum particle (hadron) detection/tracking
- Various target nuclei

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

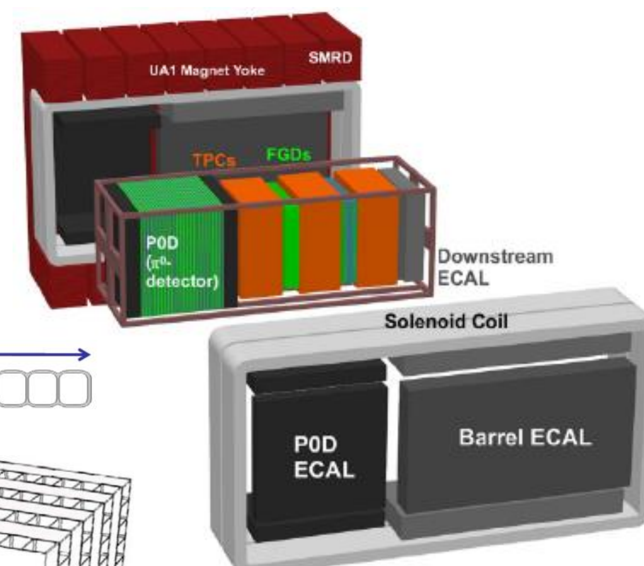


NOνA (@FNAL, NuMI)
Full active scintillator
tracking detector





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

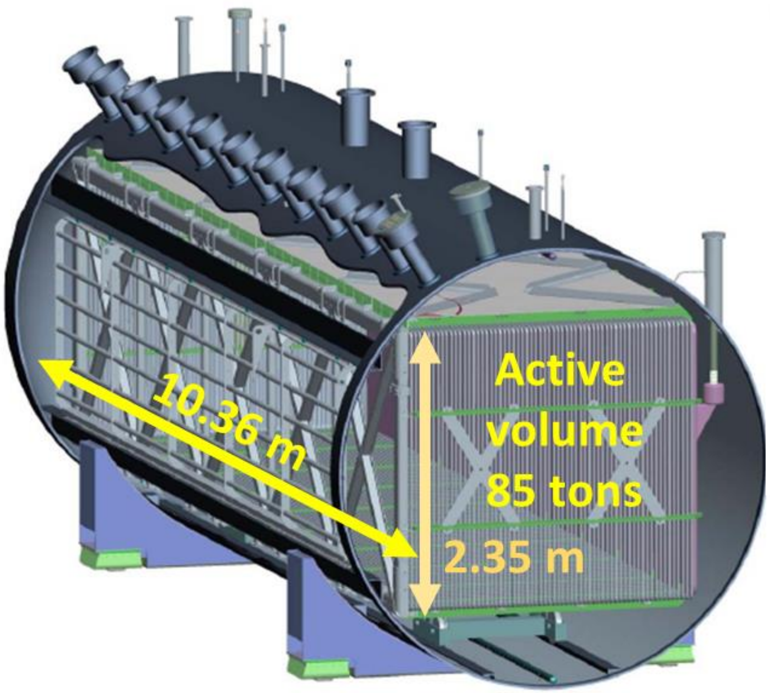


Cross-section measurements

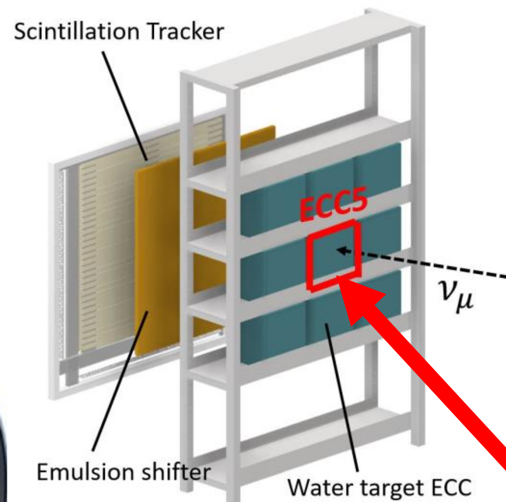
More recent experiments

- High statistics (with intense neutrino beam)
- Low momentum particle (hadron) detection/tracking
- Various target nuclei

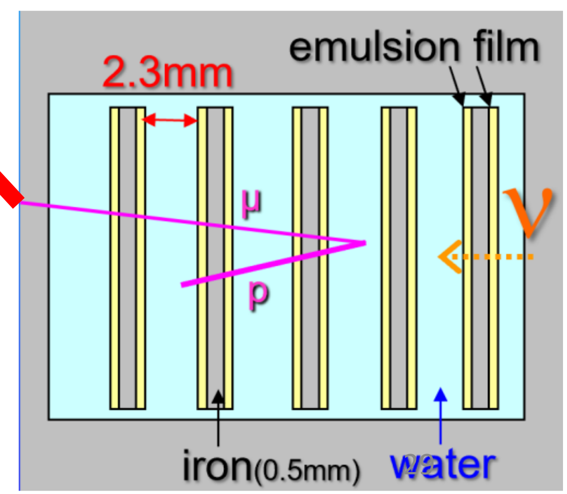
MicroBooNE (@FNAL, BNB)
Liquid argon TPC



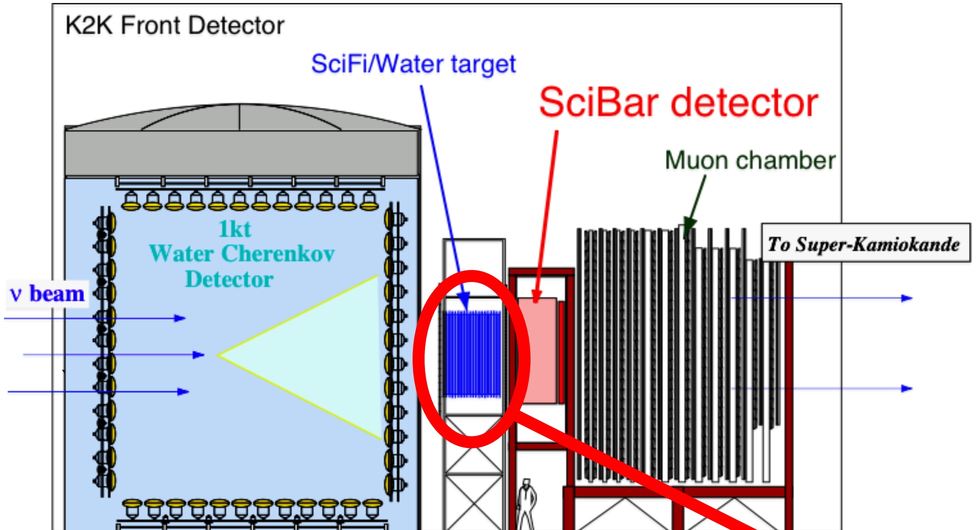
NINJA (@J-PARC)
Nuclear emulsion detector

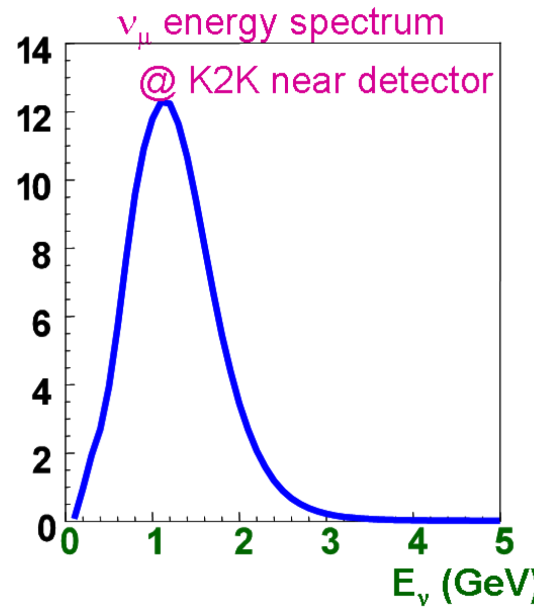


Water target
Emulsion Cloud Chamber
(ECC)



K2K Scintillating Fiber (SciFi) detector





Water in Aluminium tanks

(70% H_2O, 22% Al, 8% CH)

Angle resolution ~1deg.

μ momentum threshold

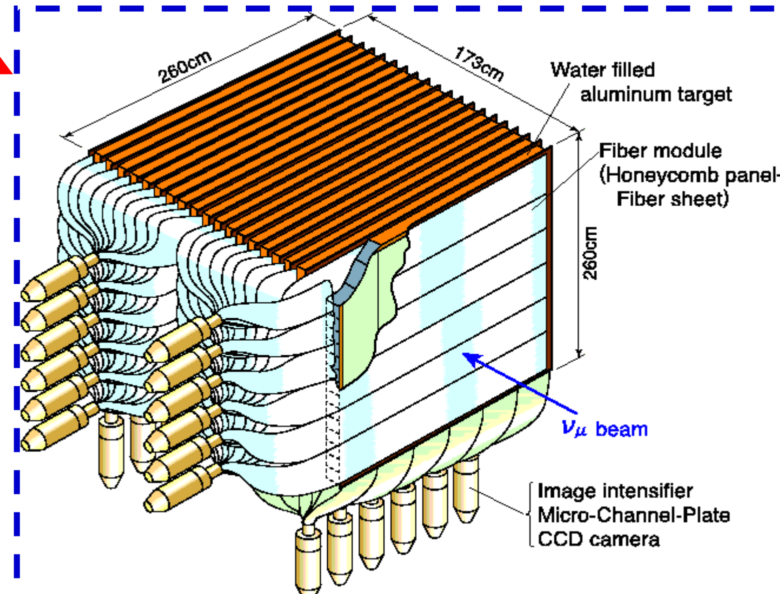
$P_\mu > 600$ MeV

(Require μ to reach MRD.)

proton momentum threshold

$P_p > 600$ MeV

(Require proton to penetrate at least three layers in SciFi.)



MiniBooNE

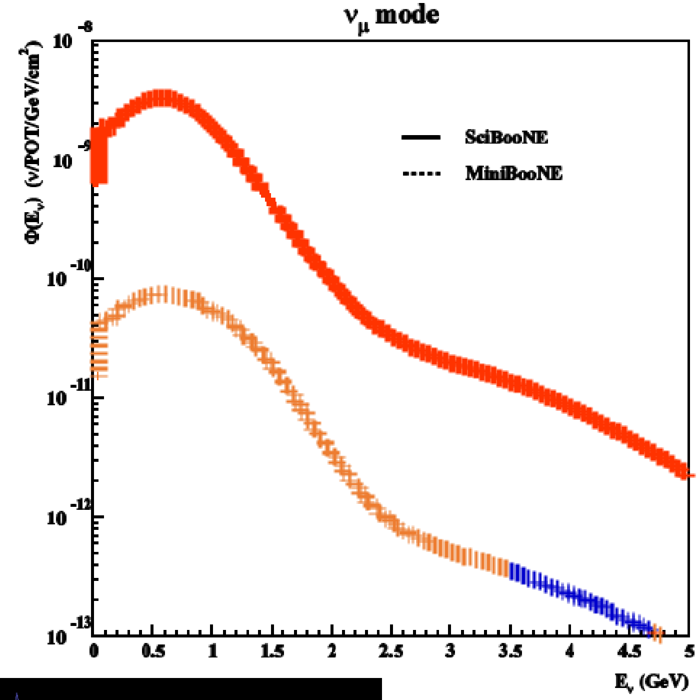
800 tons CH_2 detector

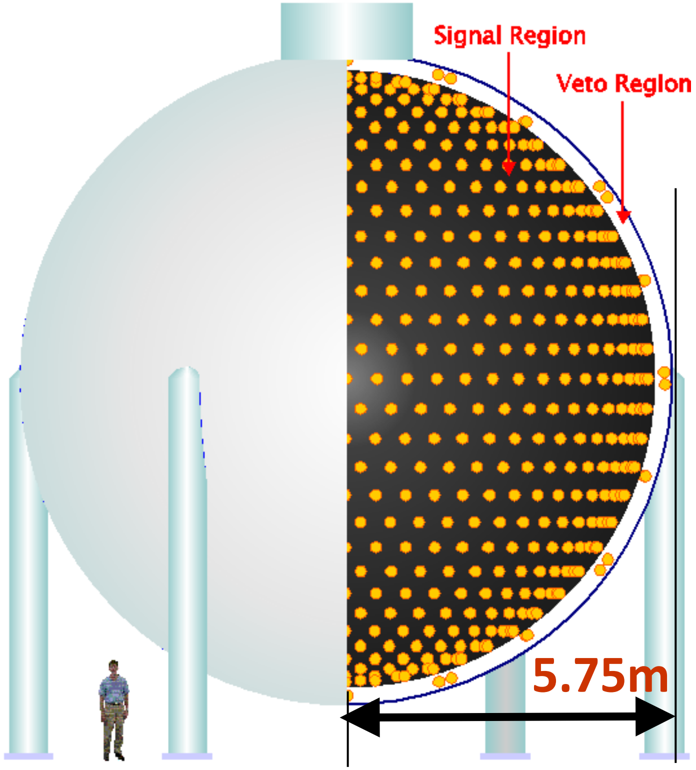
Signal region 1280 8inch PMTs

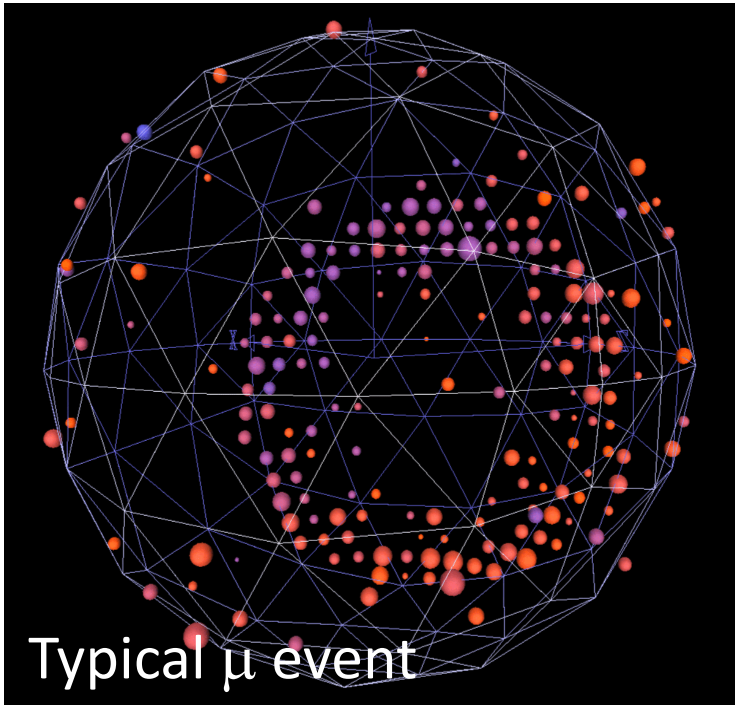
Veto region 240 8inch PMTs

Use Cherenkov and scintillation light.

T_μ > 200MeV (P_μ > ~287MeV/c)







SciBooNE

SciBar

(Used in K2K experiment)

- Full active tracking detector

  15 tons of scintillator (14336 bars)

  also acts as the interaction target.

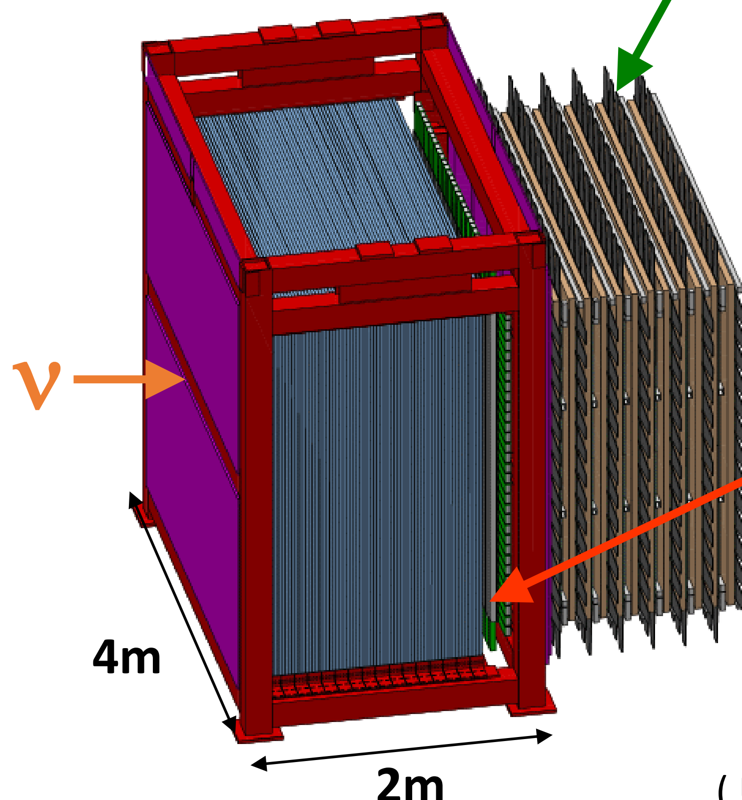
  Cell size : **2.5 x 1.3** x 300cm^3

  WLS fiber readout, 64ch MA-PMT

Muon Range Detector (MRD)

- 12 2"-thick steel layers
  + scintillator planes
  (alternate x & y)
- Measure μ momentum using range (up to ~ 1.2 GeV/c)

(Components are recycled from past experiment)



Electron Catcher (EC)

- Spaghetti calorimeter
- 2 planes (11 X_0)

  4 x 4 cm^2 cell x 128
- Identify π^0 and ν_e

(Used in CHORUS, HARP and K2K)

SciBooNE

- Full Active tracking detector

  Extruded scintillator

  with WLS fiber readout

  Cell size : **2.5 x 1.3** x 300cm^3

  Light yield :**7~20p.e.** /MIP/cm

  (2 MeV)

  → { reconstruct vertex
      identify the interaction

- High efficiency

  even for the short tracks

- Can detect

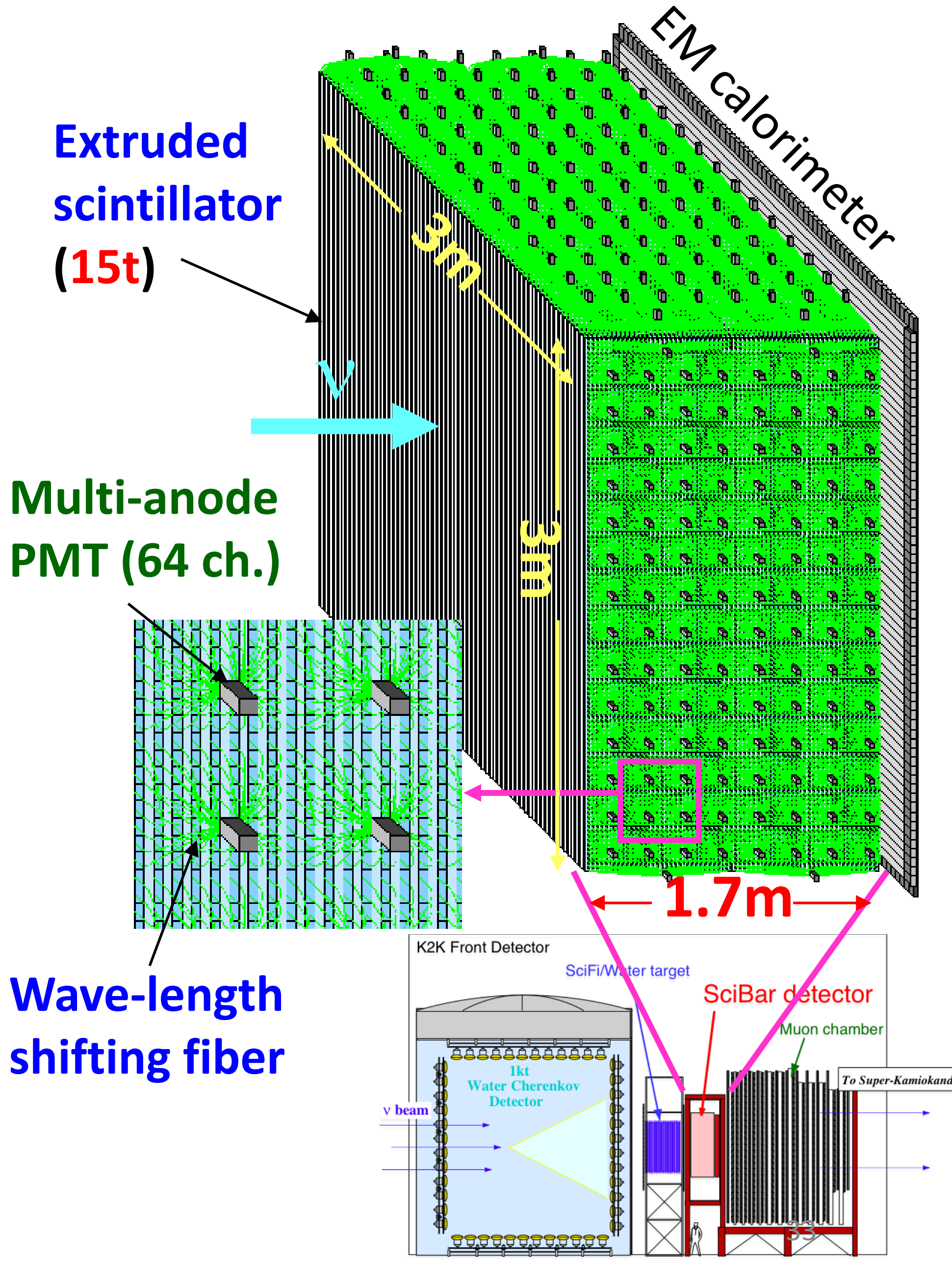
  low momentum protons

  down to ~350 MeV/c.

- PID (p/π)

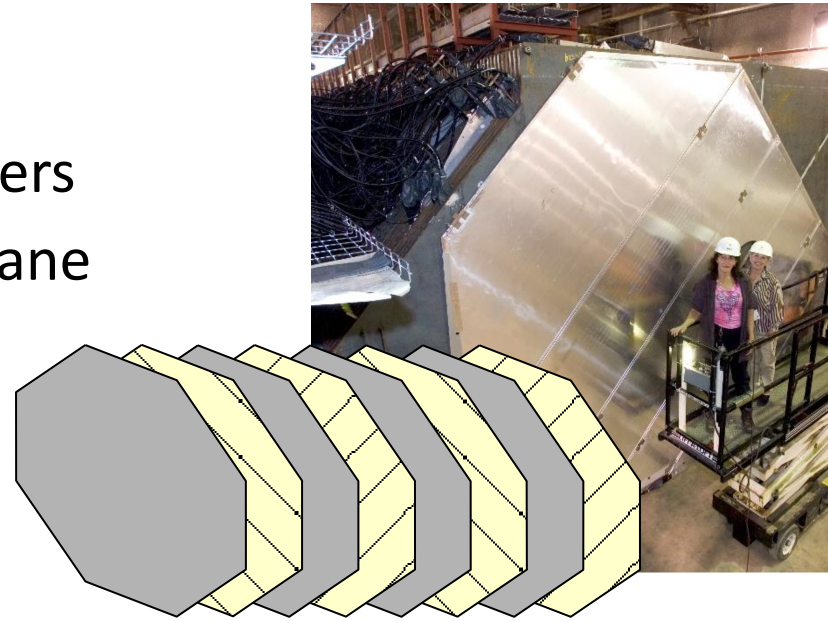
  & momentum measurement

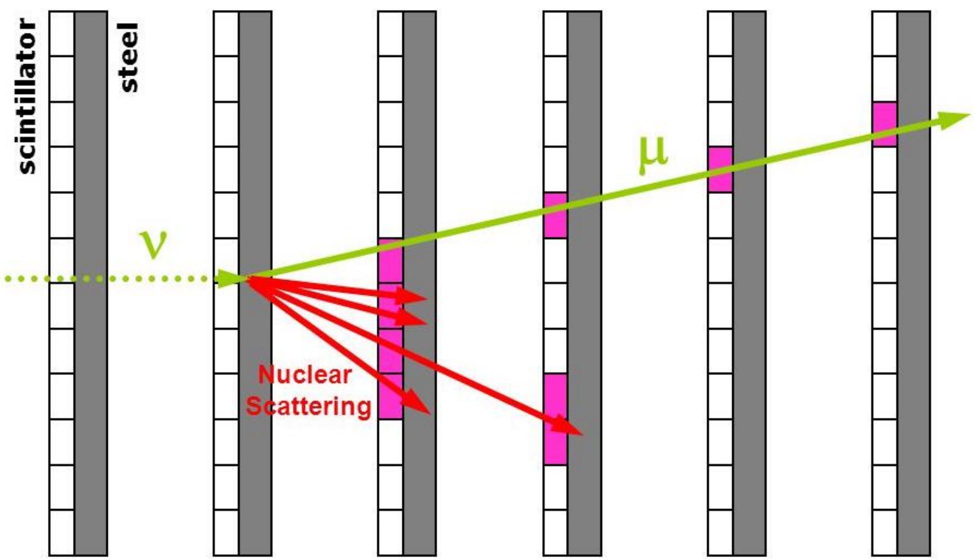
  by dE/dx.

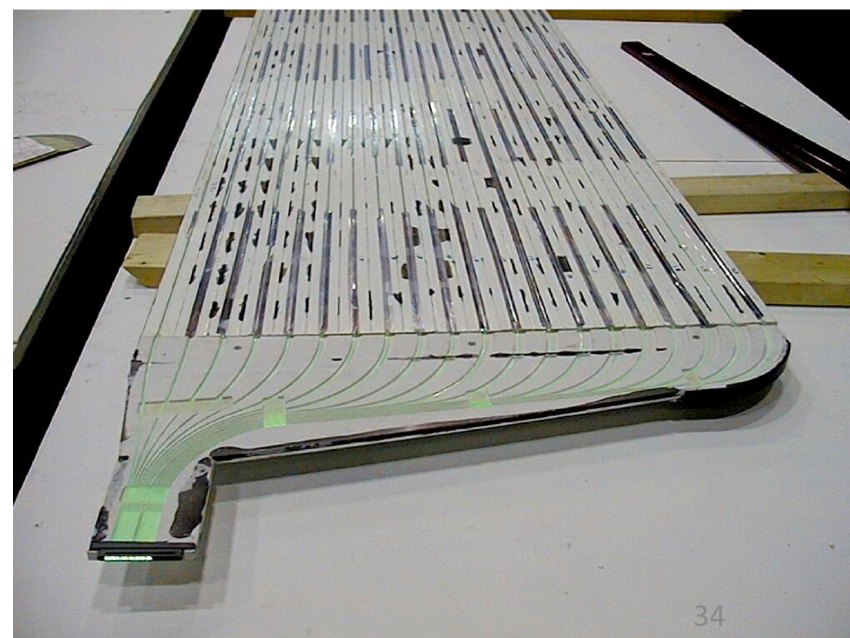


MINOS Near detector

- 980 tons Tracking sampling calorimeters
  - Stack Iron plate and scintillator plane
    Thickness of Iron plate is 2.54 cm
    Scintillator width is 4.1cm
  - With magnetic field
    Charge identification
    Momentum measurement using both curvature and track length.







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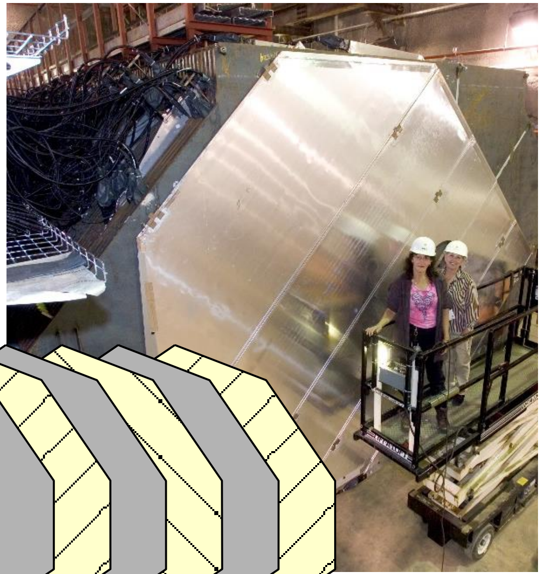
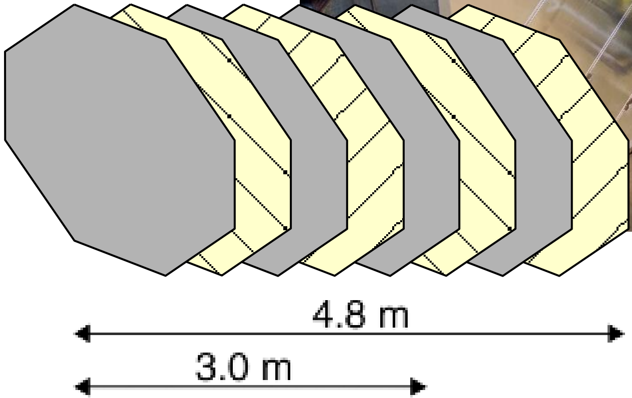
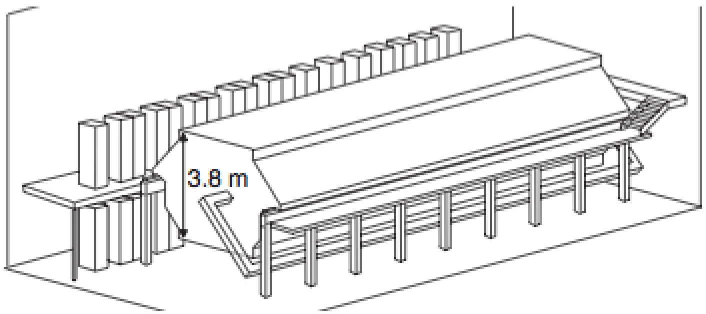
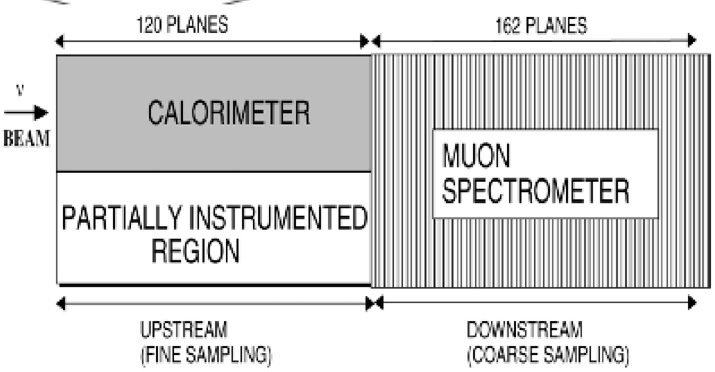
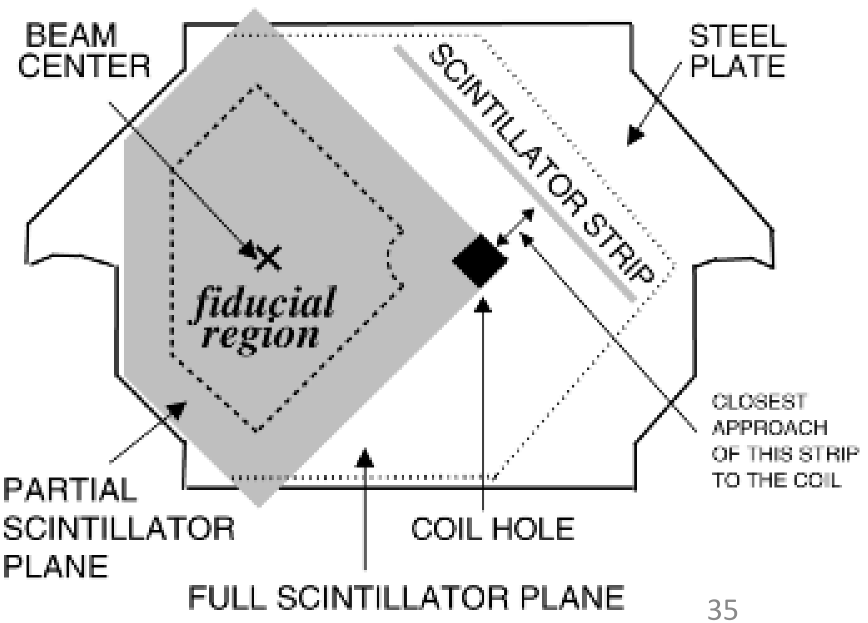






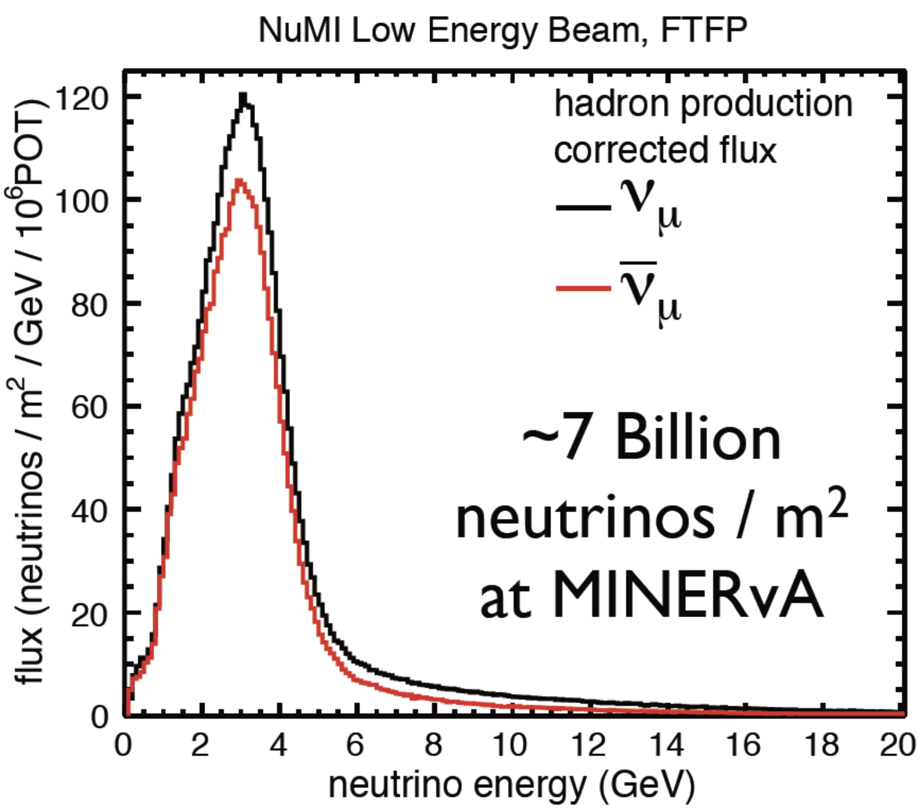




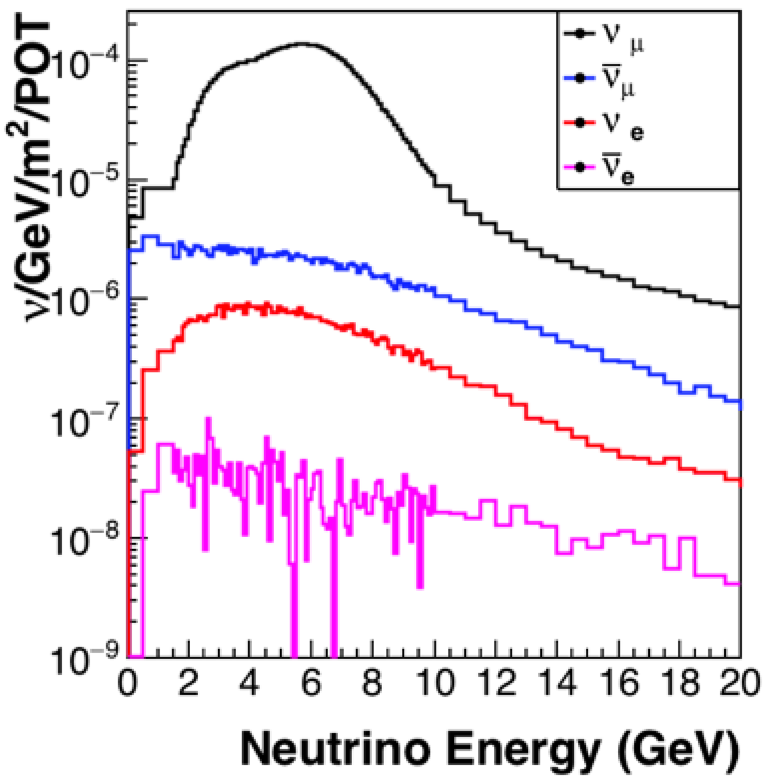
MINERνA experiment

Located in front of the MINOS near detector (NuMI beamline)

E_ν~ 3.5GeV (Low energy) or E_ν~ 6 GeV (Medium energy)



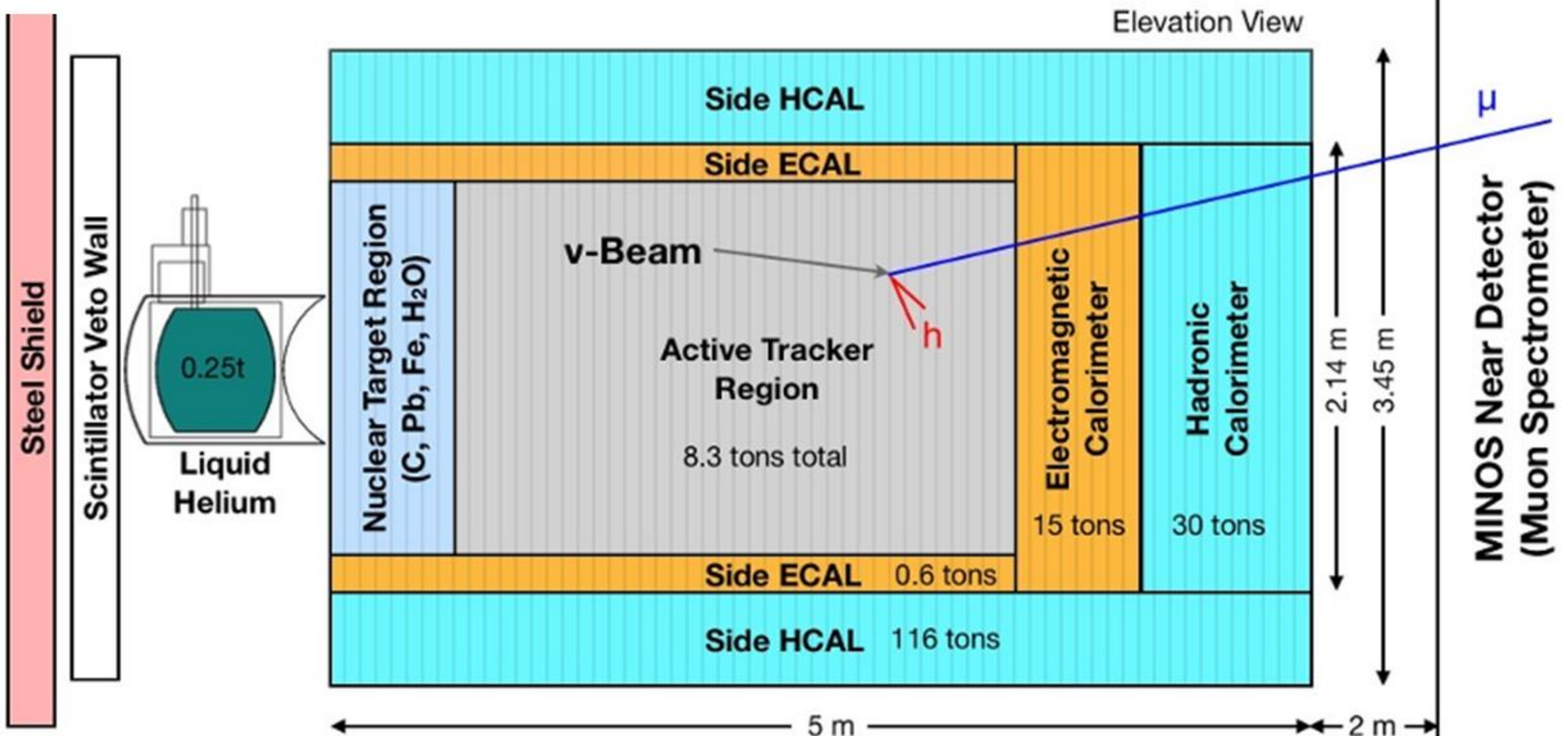
Medium energy beam



MINERνA experiment

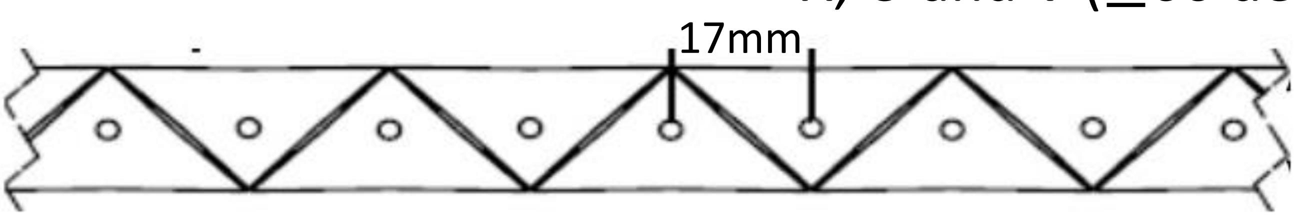
Located in front of the MINOS near detector (NuMI beamline)

Fine grained detector with various target material.



Triangular shape scintillator and three views,

X, U and V (±60 degrees)



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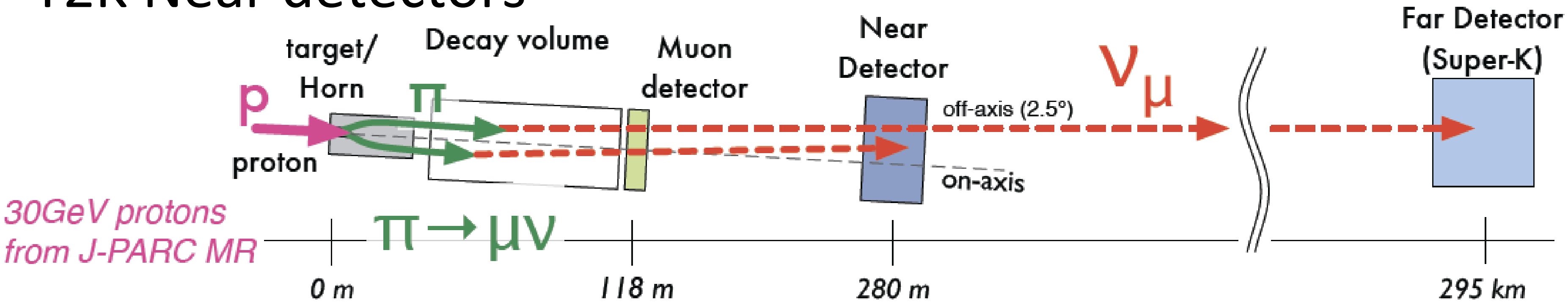
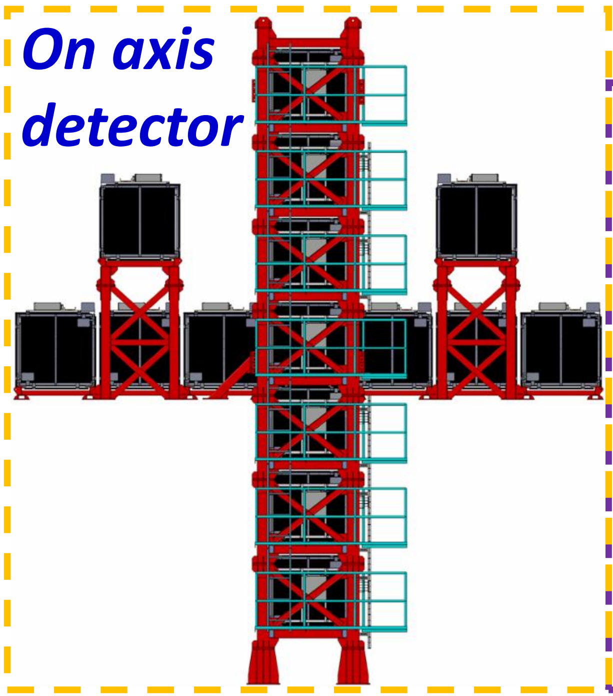
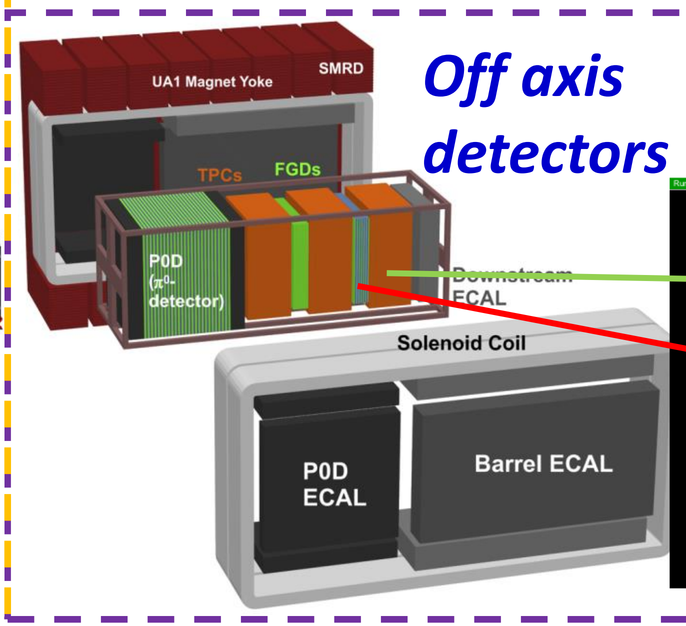
T2K Near detectors

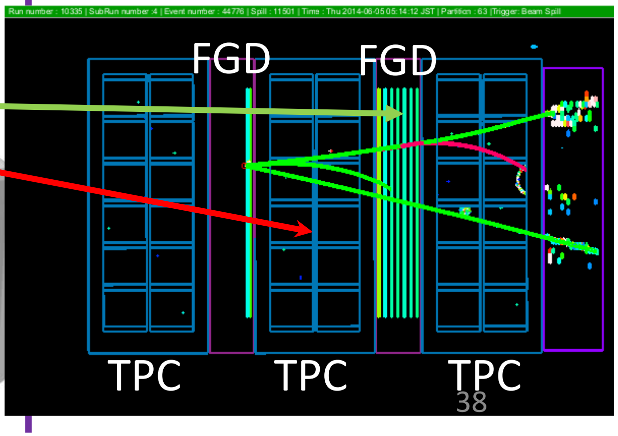


- On axis near ν detector ***INGRID***
  - ν interaction rate
  - ν beam direction monitor
- Off axis ν detectors
  - neutrino flux measurements
  - neutrino interaction studies

In the UA1 magnet (0.2 T)







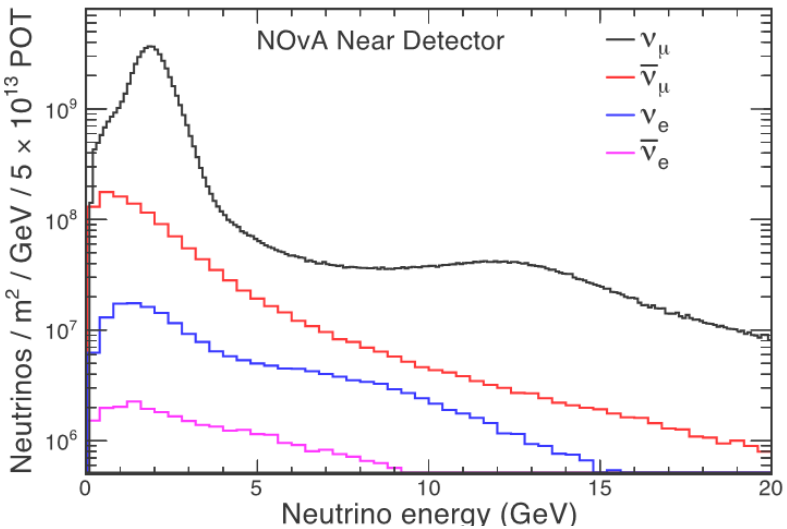
NOνA experiment

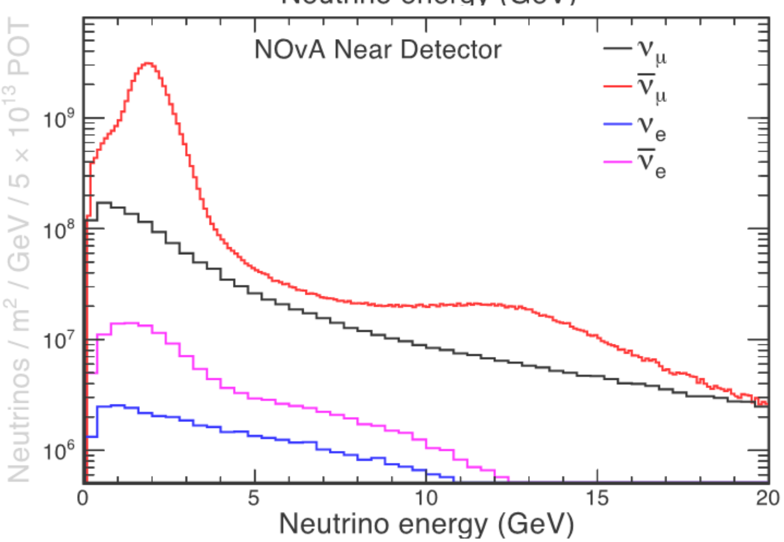
NOνA @ FNAL, NuMI off-Axis
(14.6 mrad off-axis beam)

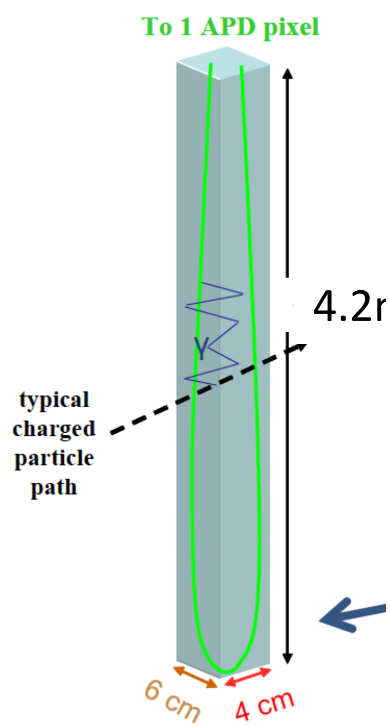
Near detector

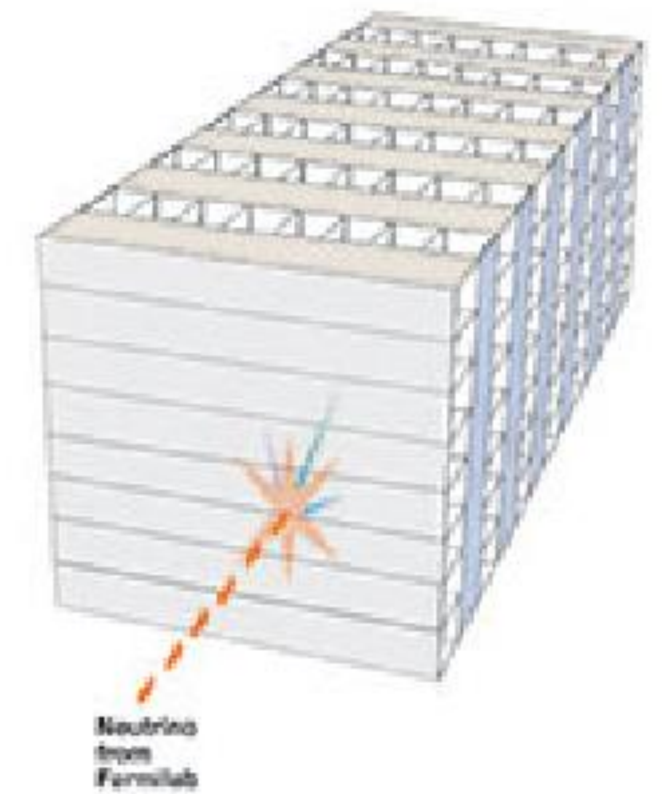
4.2m x 4.2m x 15.8m (0.3 ktons)

214 layers, 20,192 pixels



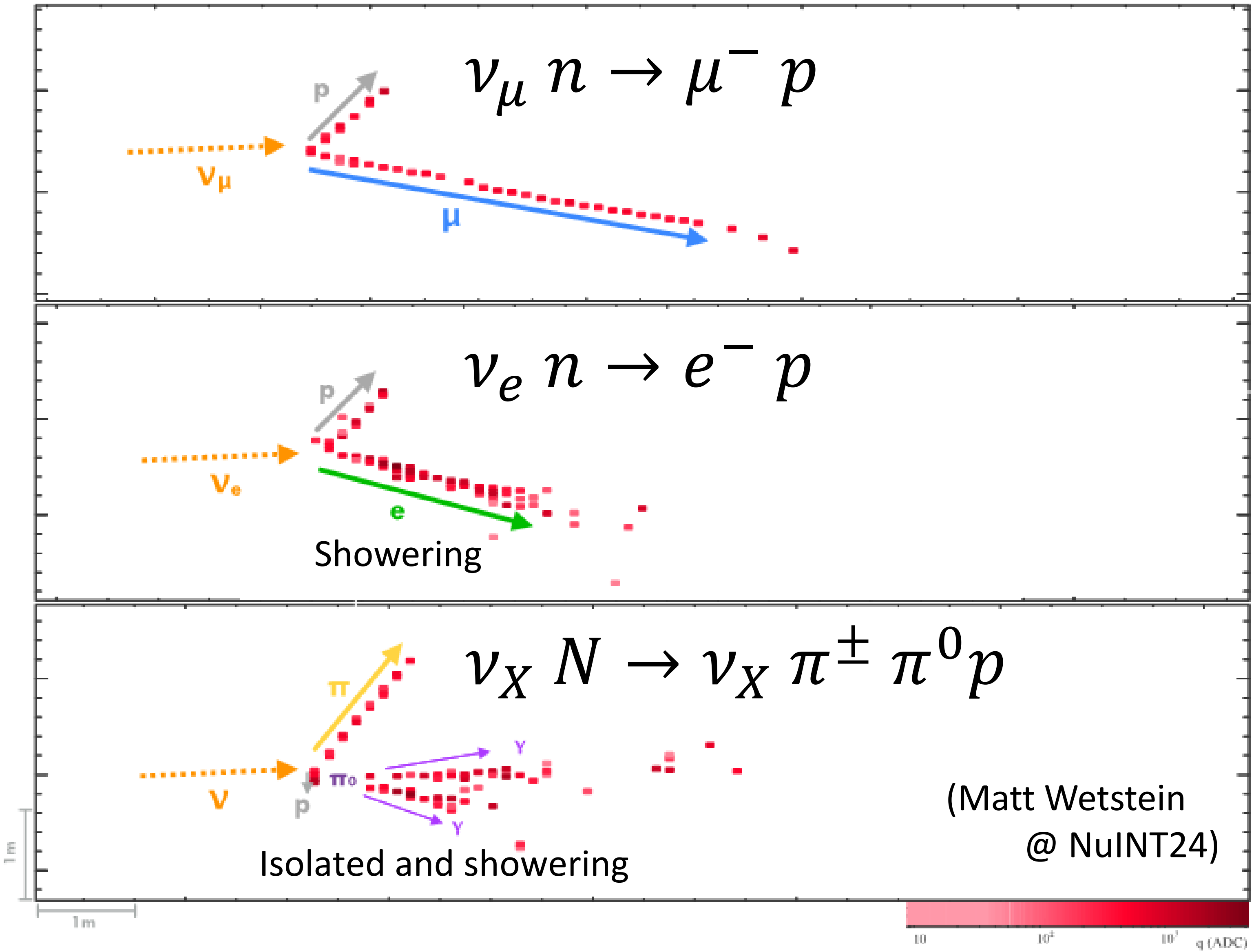






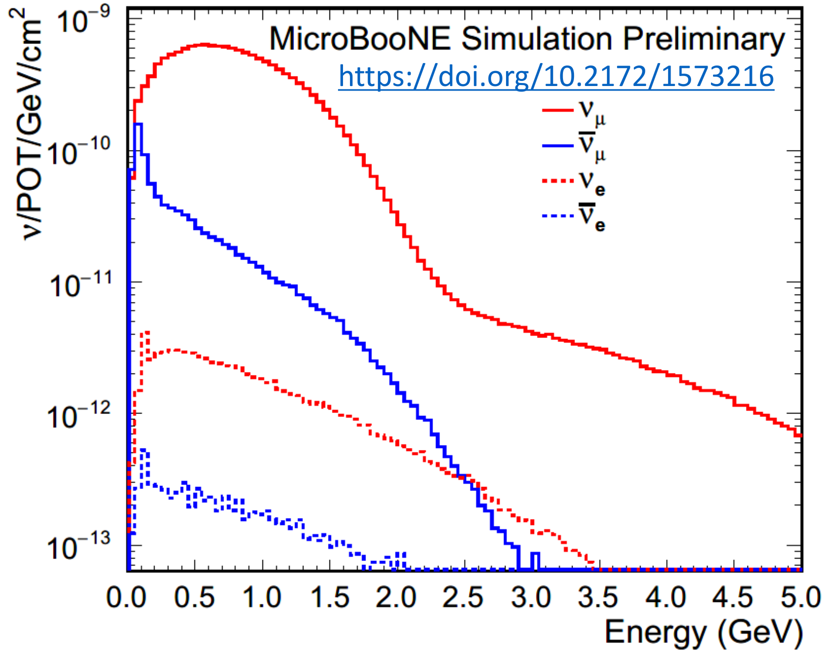
NOνA experiment

Liquid scintillator tracking detector



MicroBooNE

MicroBooNE @ FNAL, BNB (Liquid Argon TPC)

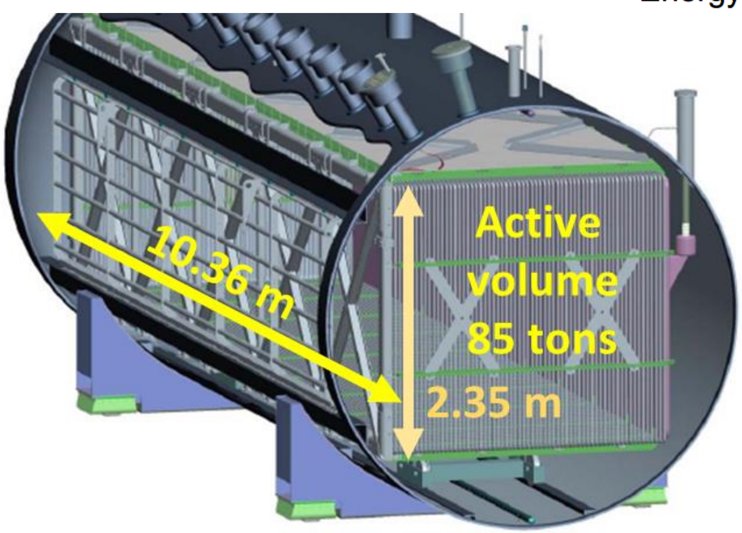


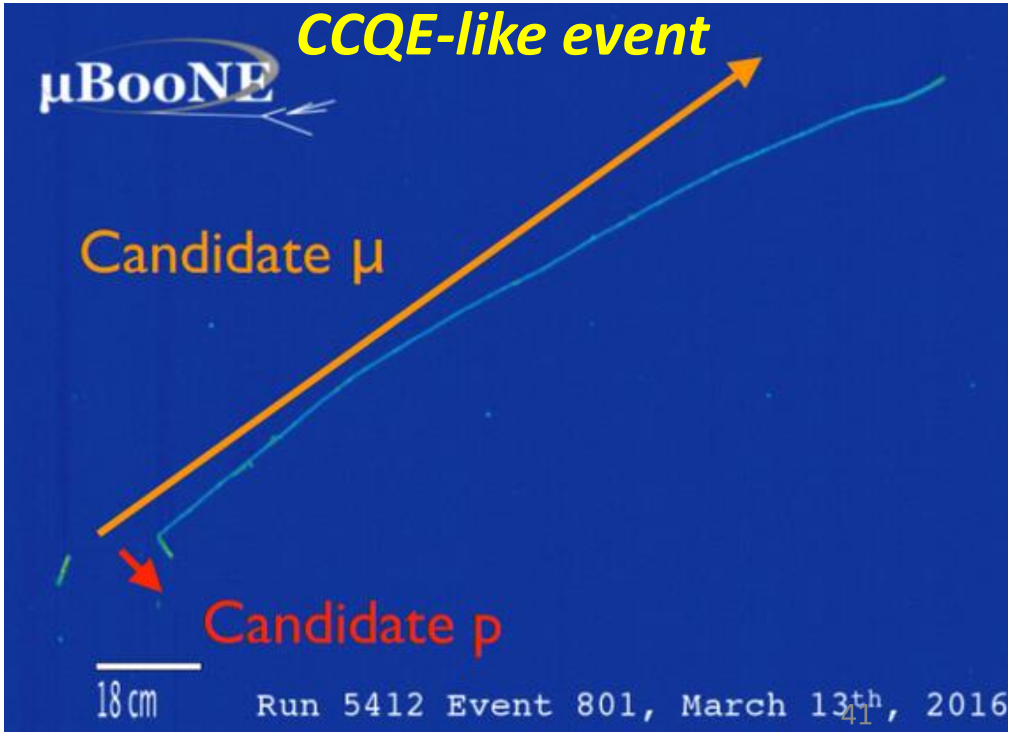
Neutrino energy is < 1 GeV

CCQE dominant region

Low proton momentum threshold

~ 300 MeV/c (E_k ~ 47 MeV)



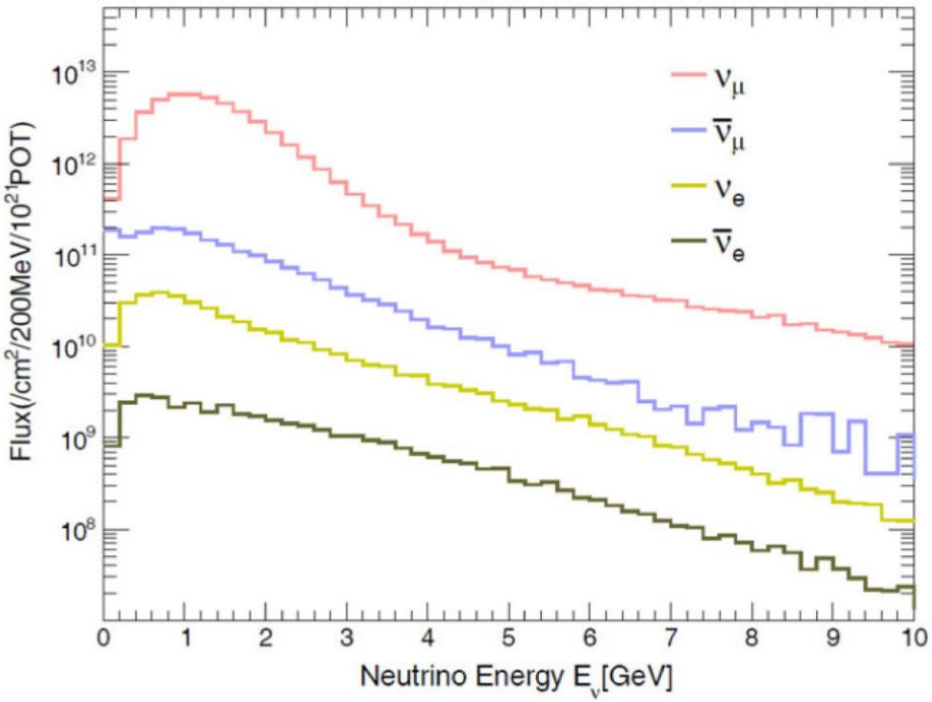


NINJA experiment

NINJA @ J-PARC MR neutrino beamline

Mean E_{ν} ~ 1.49 GeV

CCQE & single π production



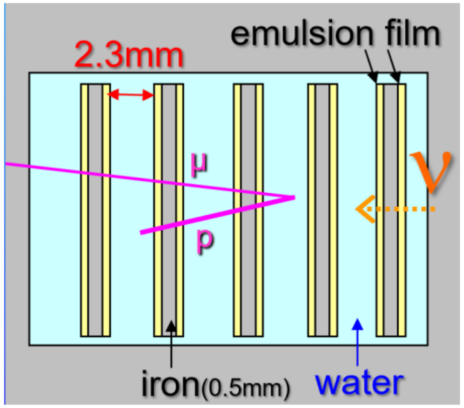
Low hadron momentum threshold

Proton ~ 200 MeV/c

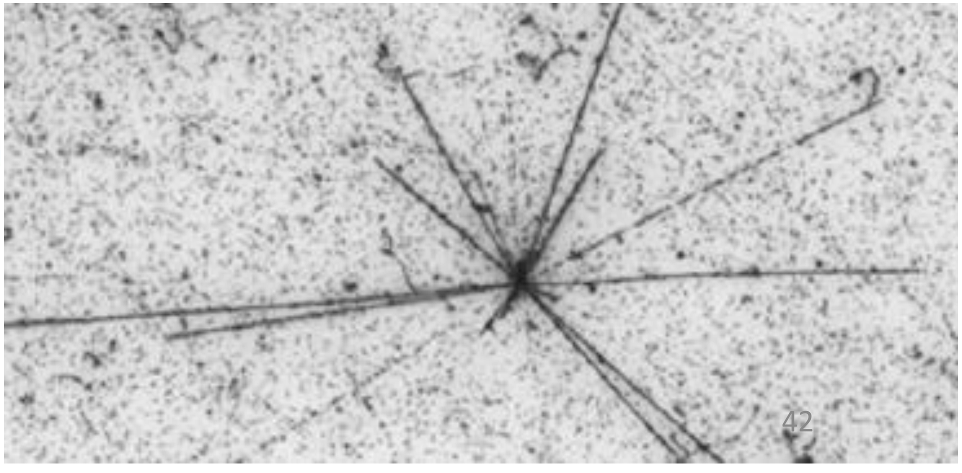
Charged pion ~ 50 MeV/c

Nuclear emulsion detector

Emulsion films are inserted between the target material.

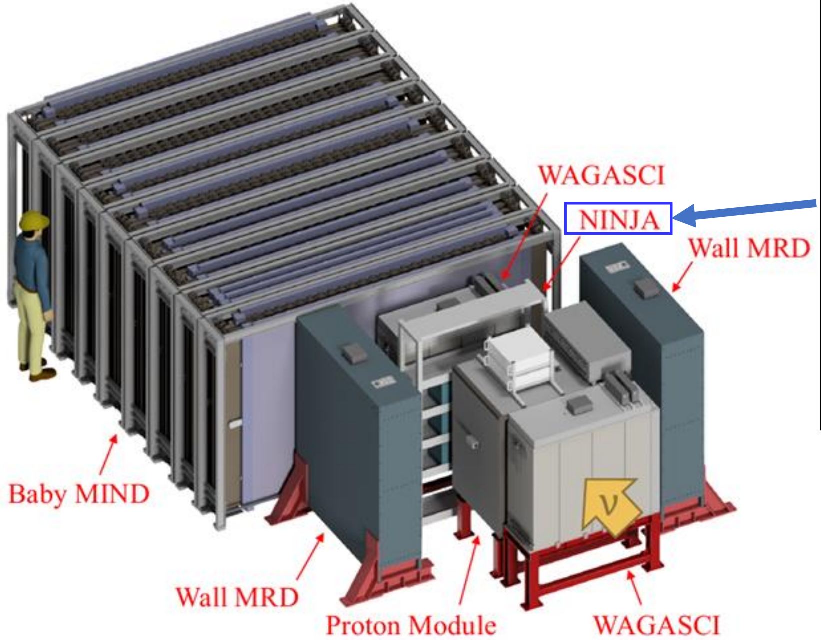


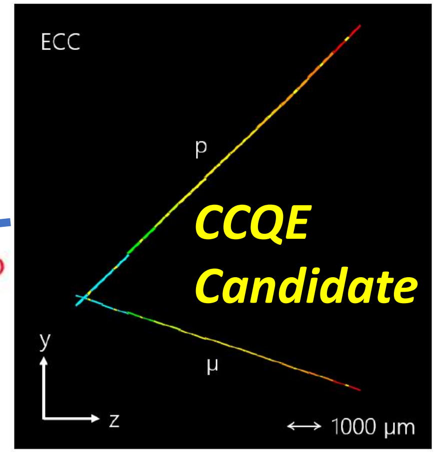
Example of multiple track event

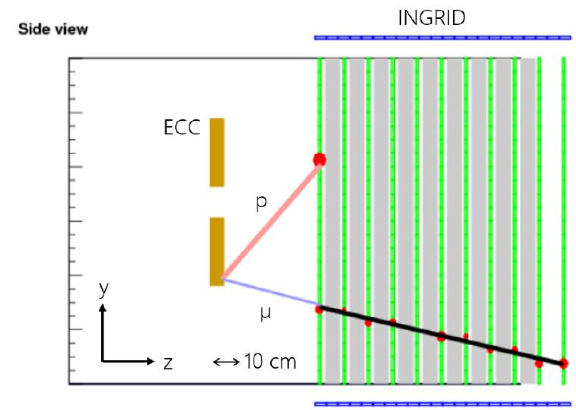


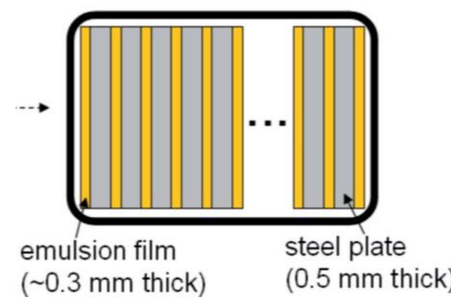
NINJA experiment

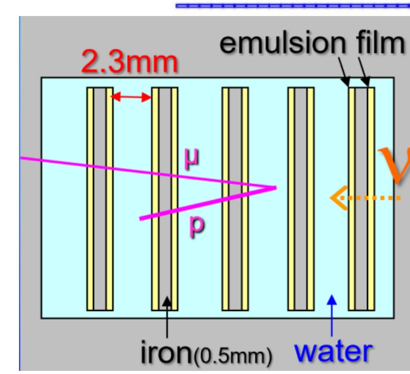
NINJA @ J-PARC MR neutrino beamline







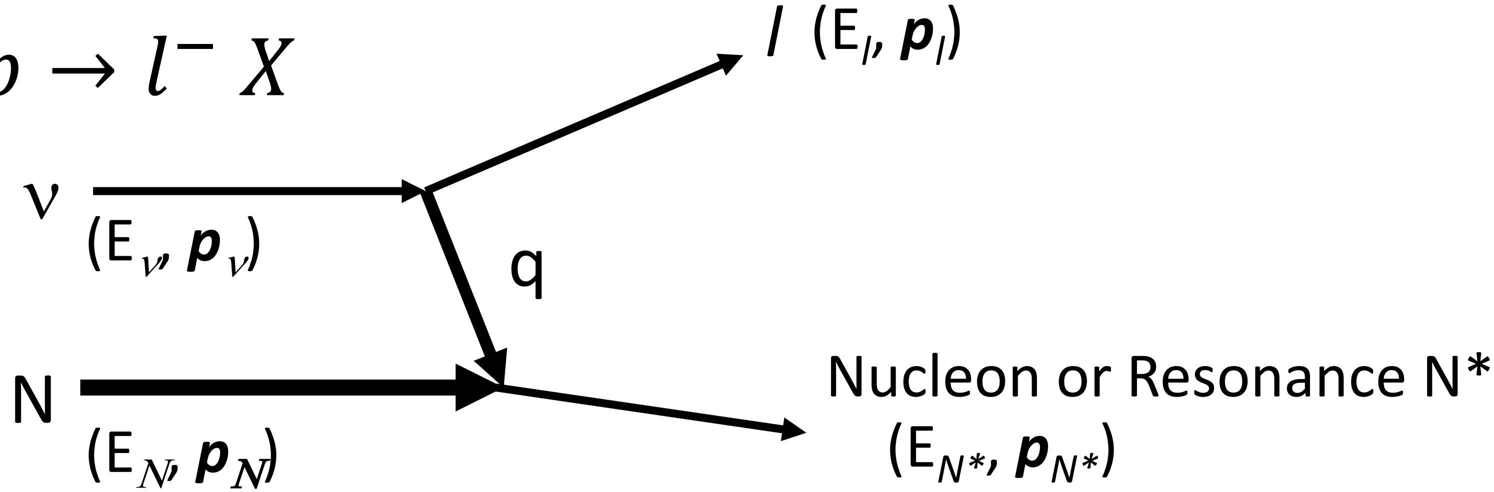




Emulsion films can be inserted in various target material.
Main emulsion detector does not provide timing information.
Also, the size is small, and particles escapes from the detector easily.
Need to be combined with the other time stamper
and tracking detectors.

Frequently used variables

$$\nu\, p \to l^- X$$



ω (ν) : Energy transfer

$$\omega = \nu \equiv E_l - E_\nu$$

q^2 : 4 momentum transfer

$$q^2 \equiv (E_l - E_\nu)^2 - (\boldsymbol{p}_l - \boldsymbol{p}_\nu)^2$$

$(= -Q^2)$

W : Invariant Mass of N*

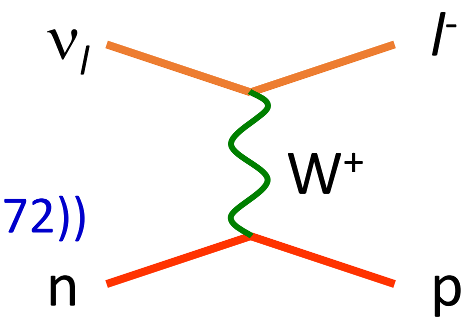
$$W \equiv \sqrt{E_{N*}^2 - p_{N*}^2}$$

$$x \equiv \frac{Q^2}{2P_N \cdot q} = \frac{Q^2}{2M\nu}$$

(Bjorken x)

$$y = \frac{p_N \cdot q}{p_N \cdot p_\nu} = \frac{\nu}{E_\nu}$$

Charged current quasi-elastic scattering



Cross-section formulation

Free nucleon : C.H.L. Smith (Phys. Rep. 3,261(1972))

$$\mathcal{H}_{int} = \frac{G}{\sqrt{2}} J_\alpha^{lep} J_{had}^\alpha + h.c.$$

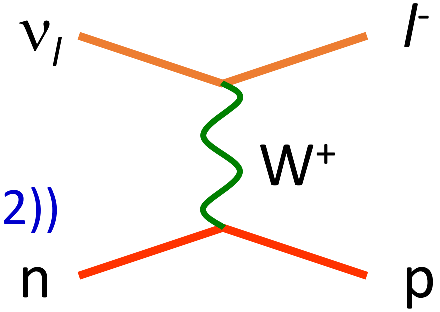
$$< \mu(k')|J_\alpha^{lep}|\nu_\mu(k) >= \bar{u}(k')\gamma_\alpha(1-\gamma_5)u(k), \quad J_{had}^\alpha = \cos\theta_C(V^\alpha - A^\alpha).$$

$$\frac{d\sigma_{\nu,\bar{\nu}}}{dQ^2} = \frac{G^2\cos^2\theta_C M^2}{8\pi E^2}\left(A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\left(\frac{s-u}{M^2}\right)^2\right)$$

$A(Q^2), B(Q^2), C(Q^2)$ are described as functions of vector, axial-vector and pseudo-scaler form factors.

- Vector form factors (F_V)
  Determined by the electron scattering experiments.
  Quite precisely measured.
- Axial vector form factor (F_A)
  Determined by the neutrino scattering experiments.
  Thought to be "measured".

Charged current quasi-elastic scattering



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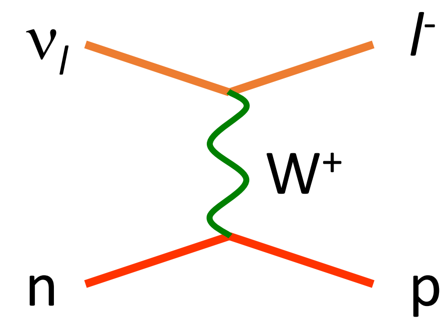
$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[(4+\frac{Q^2}{M^2})F_A^2 - (4-\frac{Q^2}{M^2})F_V^2 + \frac{Q^2}{M^2}(1-\frac{Q^2}{4M^2})F_M^2\right.$$

$$\left. +4\frac{Q^2}{M^2}F_V F_M - \frac{m^2}{M^2}\left((F_V+F_M)^2 + (F_A+2F_P)^2 - (4+\frac{Q^2}{M^2})F_P^2\right)\right]$$

$$B(Q^2) = \frac{Q^2}{M^2}F_A(F_V+F_M) \qquad C(Q^2) = \frac{1}{4}\left(F_A^2 + F_V^2 + \frac{Q^2}{4M^2}F_M^2\right)$$

$$(s - u = 4ME_{\nu} + q^2 - m^2)$$

Charged current quasi-elastic scattering



Typical signatures of ν_μ and $\overline{\nu_\mu}$ CCQE

$$\nu_\mu \, n \to \mu^- \, p, \overline{\nu_\mu} \, p \to \mu^+ \, n$$

- Neutrino case

1) One (negative) charged lepton with one proton.
2) One (negative) charged lepton without any other "visible" hadrons.

- Anti neutrino case

1) One (positive) charged lepton with neutron.
2) One (positive) charged lepton without any other "visible" hadrons.

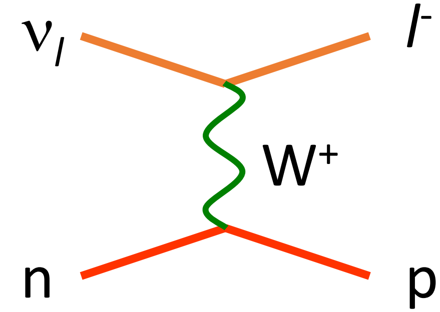
We "may" require the existence of one decay electron.

$$\mu^- \to \; e^- \, \overline{\nu_e} \, \nu_\mu, \mu^+ \to \; e^+ \, \nu_e \, \overline{\nu_\mu}$$

But μ^- may be captured.

Also, detection efficiency (detector) is not 100%.

Charged current quasi-elastic scattering

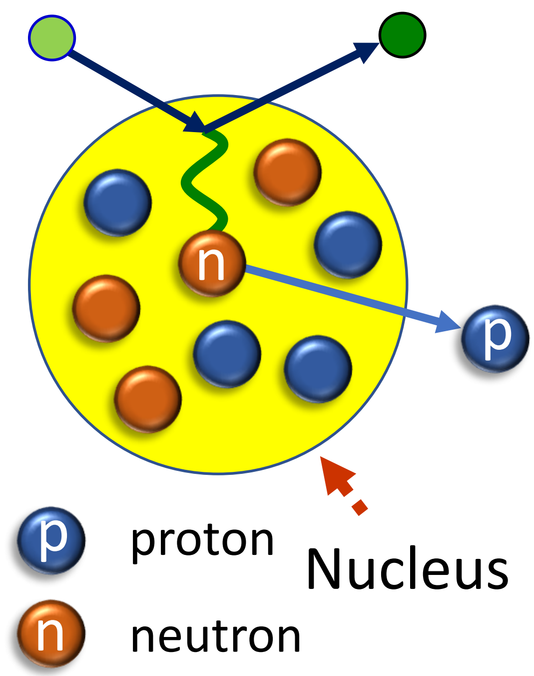


Why are the bubble chamber results used as “reference”?

The target was D_2. (Not all the experiments.)

Neutron target with minimum nuclear effects.

Possible nuclear effects with larger nucleus:

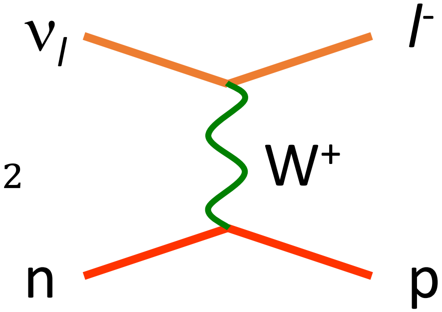


- Target neutron is bound in nucleus.
- Scattered proton may re-interact in nucleus before escaping. (Direction and momentum may be changed, may kick out the other nucleons, may produce the other particles, like pions.)

$$(p\, N \rightarrow N' N'' \pi)$$

- Scattered proton may interact in the detector medium.
- Additional particles generated by non CCQE interaction may interact and become invisible.

Charged current quasi-elastic scattering

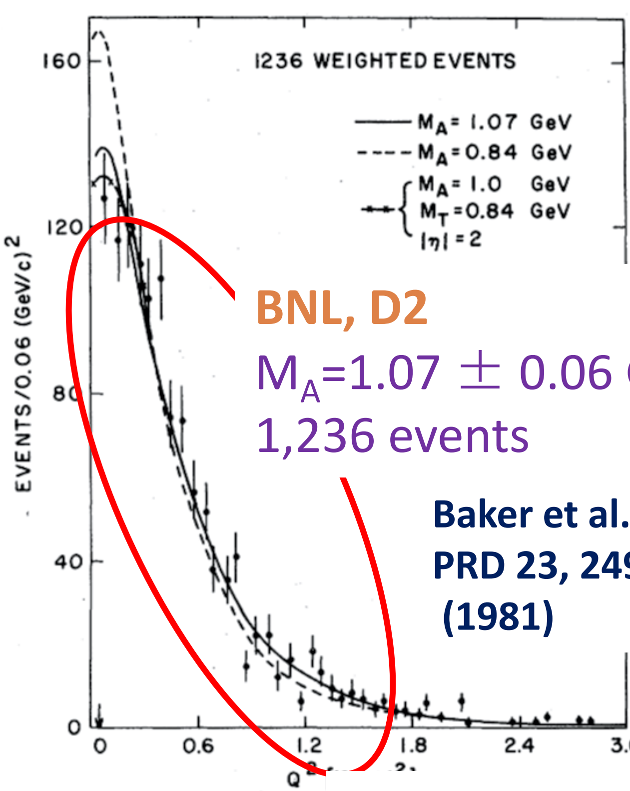


Axial vector form factor

Assumed dipole form. $$F_A(q^2) = F_A(0) \times \left(1 - \frac{q^2}{M_A^2}\right)^{-2}$$

$F_A(0) \sim 1.267$ (From β decay)

Mainly, bubble chamber (mainly D_2) data were used to obtain M_A.



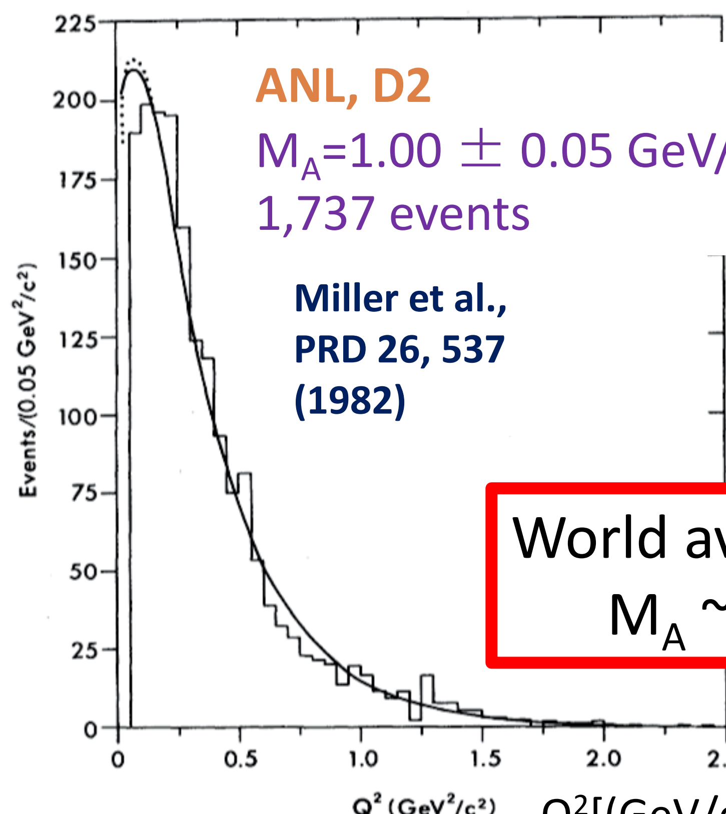
BNL, D2

M_A=1.07 ± 0.06 GeV/c²

1,236 events

Baker et al., PRD 23, 2499 (1981)

Q^2[(GeV/c)²]



ANL, D2

M_A=1.00 ± 0.05 GeV/c²

1,737 events

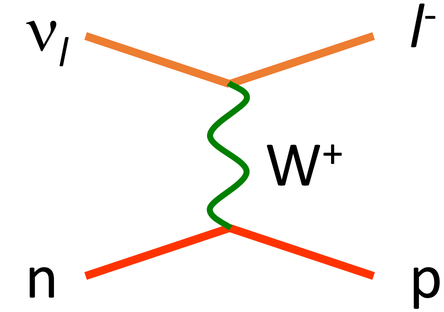
Miller et al., PRD 26, 537 (1982)

Q^2[(GeV/c)²]

World average

M_A ~ 1.03 GeV/c²

Charged current quasi-elastic scattering



Example of the other experiments

MiniBooNE (Oil Cherenkov detector)

Select single “muon like” ring event with one decay electron.

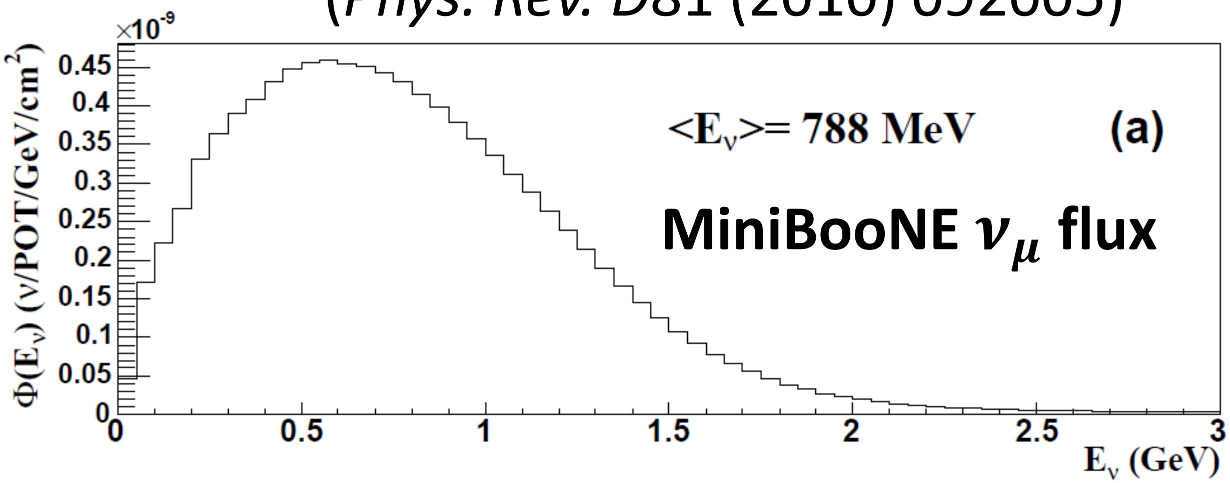
Advantage of ring imaging “Cherenkov” detectors

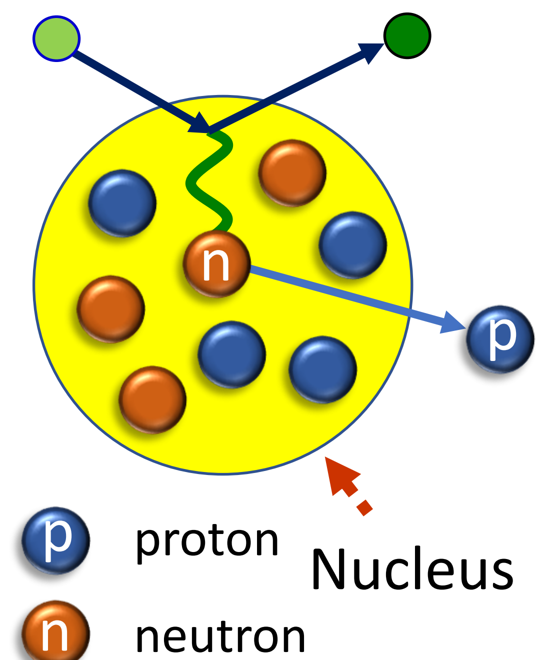
Angular coverage is large.

The energy threshold of μ is quite small.

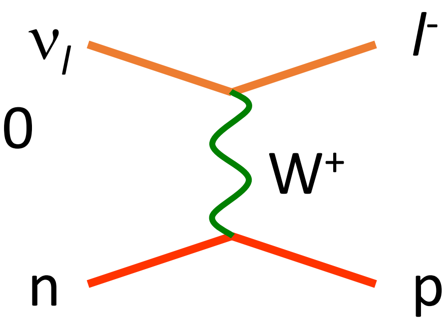
Purity of CCQE was estimated to be 77% and efficiency was 26.6%.

(*Phys. Rev. D*81 (2010) 092005)





Charged current quasi-elastic scattering



K2K and the following "new" experiments after 1990 found discrepancies.

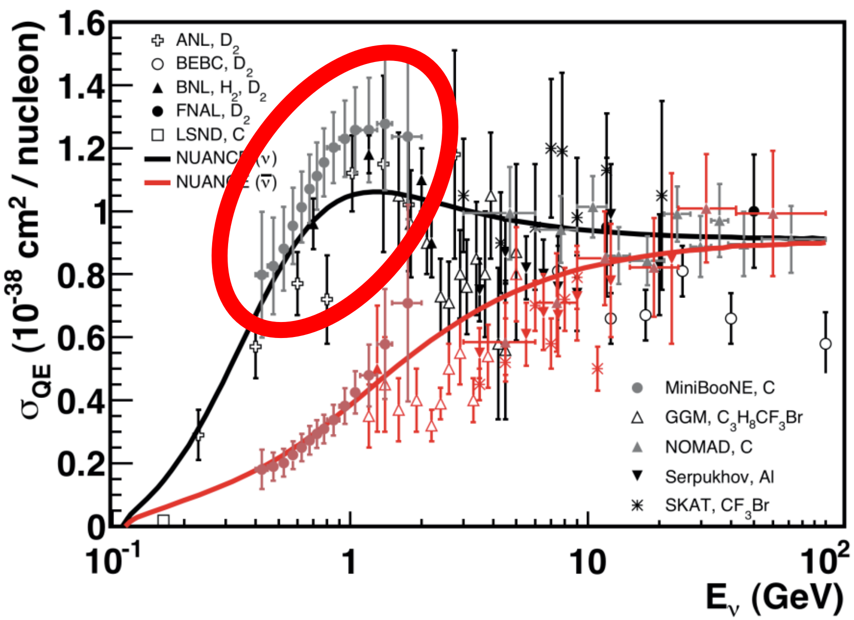
- Strong "forward going" μ suppression.

  Stronger suppression in the small q^2 region.
- Larger number of "CCQE-like" event rate (10 ~ 30%)

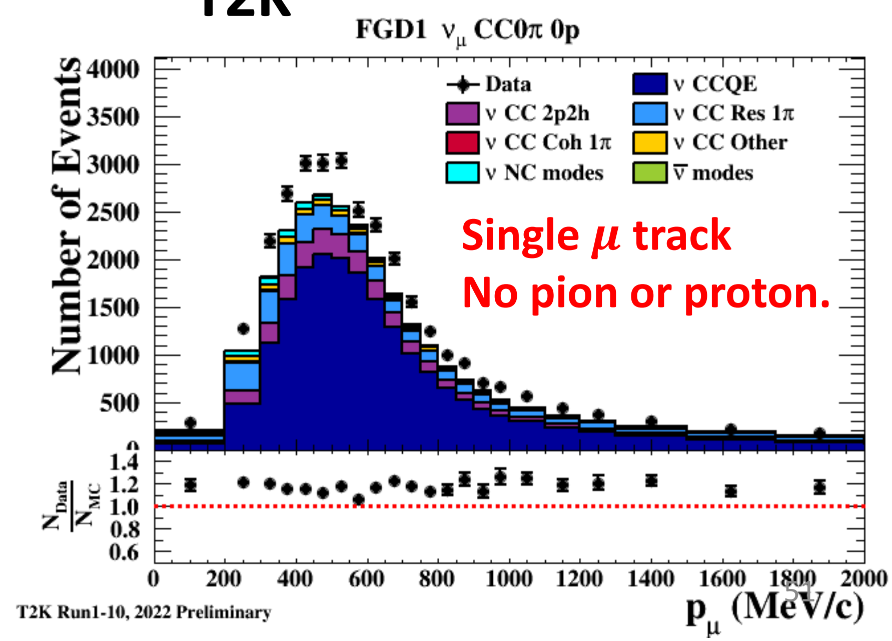
Limited sensitivity to low momentum hadrons.

-> ***Limitation from the detectors.***

MiniBooNE



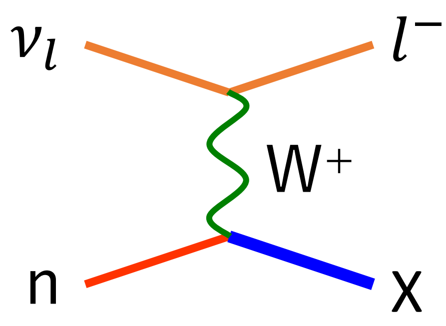
T2K



Charged current quasi-elastic scattering

Dominant interaction in a few hundred MeV.

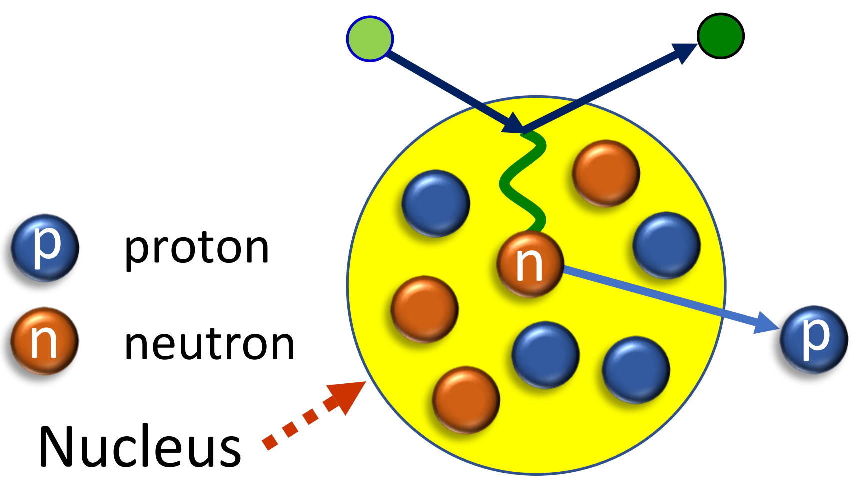
$$\nu\, n \to l^- \, p$$
$$\bar{\nu}\, p \to l^+ \, n$$



Experiments after the late 1990's found discrepancies.

- Fraction of forward going charged leptons in ***CCQE-like events*** is **smaller** than expected.
- # of ***CCQE-like*** events is **larger** than expected.

Modern neutrino experiments use "**nuclear target**."



Initial "nucleon" is bound in the target nucleus.

Scattered (produced) nucleon is in the nuclear medium.

Hadrons may interact in nucleus.

"Nuclear effects"

Charged current quasi-elastic scattering

Dominant interaction in a few hundred MeV.

$$\nu\, n \rightarrow l^-\, p$$
$$\bar{\nu}\, p \rightarrow l^+\, n$$

Experiments after the late 1990's found some discrepancies.

Possible sources of discrepancies

1) Nuclear modeling (binding effects)
   - Changes the allowed kinematical ranges and distributions.
2) Neutrino-nucleon interaction modeling (axial vector form factor)
   - Changes the expected event rates and distributions.
   - Parameter is determined (mainly) by the old bubble chamber neutrino experiments in the 70's and 80's.

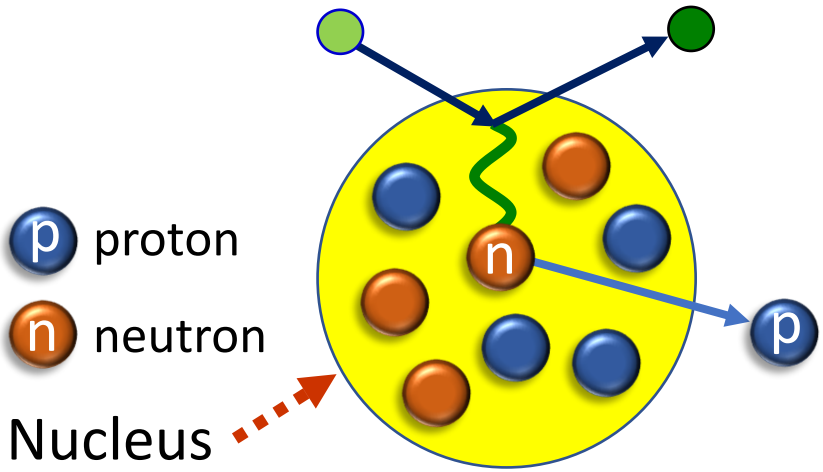
   Axial vector form factor (dipole) $F_A(q^2) = -\frac{1.276}{(1-(q^2/{M_A}^2))^2}$

   It is easy to change M_A, gives reasonable agreements with data, and thus, is used as an "effective" parameter.
3) Missing interactions which are observed as CCQE-like
   - Easily change the expected event rates and distributions.

Charged current quasi-elastic scattering

1) Nuclear modeling (binding effects)

$$\nu\, n \rightarrow l^-\, p$$
$$\bar{\nu}\, p \rightarrow l^+\, n$$



Differential cross-section is large at small 4-momentum transfer (q^2).

Sensitive to various "nuclear" binding effects.

Outgoing nucleon is also re-scattered in the nucleus.

Several models have been proposed and are being tested.

- Fermi-gas
  Considering nucleon-nucleon correlations
- Spectral function
  Considering nuclear medium effects
- Relativistic mean-field (RMF) approaches
- Super-scaling model with RMF
- ...

Charged current quasi-elastic scattering

1) Nuclear modeling (binding effects)

Study @ MicroBooNE

arXiv:2310.06082

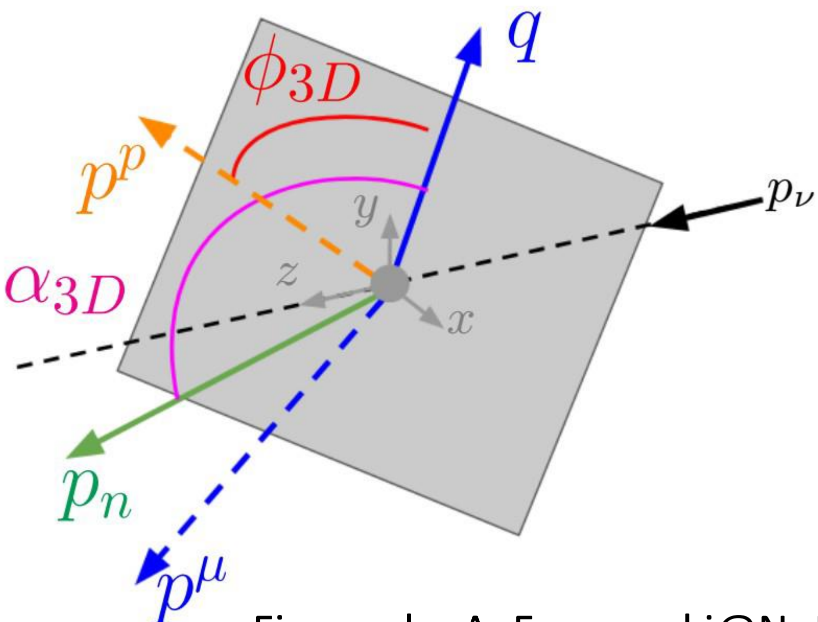
$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2},$$

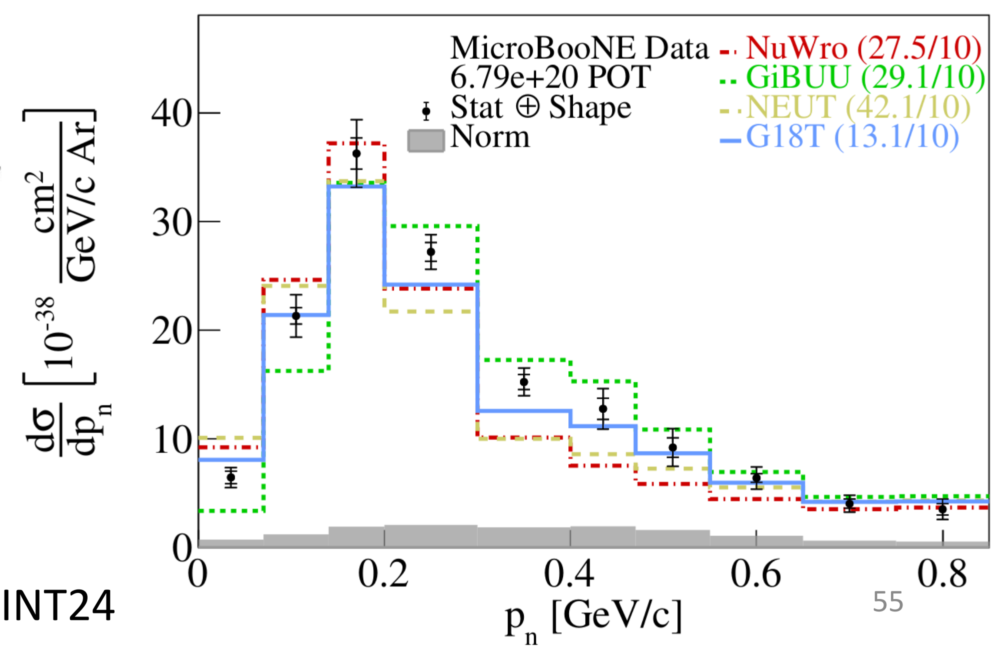
$$\phi_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_p}{|\vec{q}||\vec{p}_p|}\right),$$

$$\alpha_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_n}{|\vec{q}||\vec{p}_n|}\right).$$

Select CCQE like events

- One muon (100 – 1200 MeV/c)
- One proton (300 – 1000 MeV/c)
- No charged pions over 70 MeV/c
- No neutral pions or heavier mesons
- Any number of neutrons





Figures by A. Furmanski@NuINT24

Charged current quasi-elastic scattering

1) Nuclear modeling (binding effects)

Study @ MicroBooNE

arXiv:2310.06082

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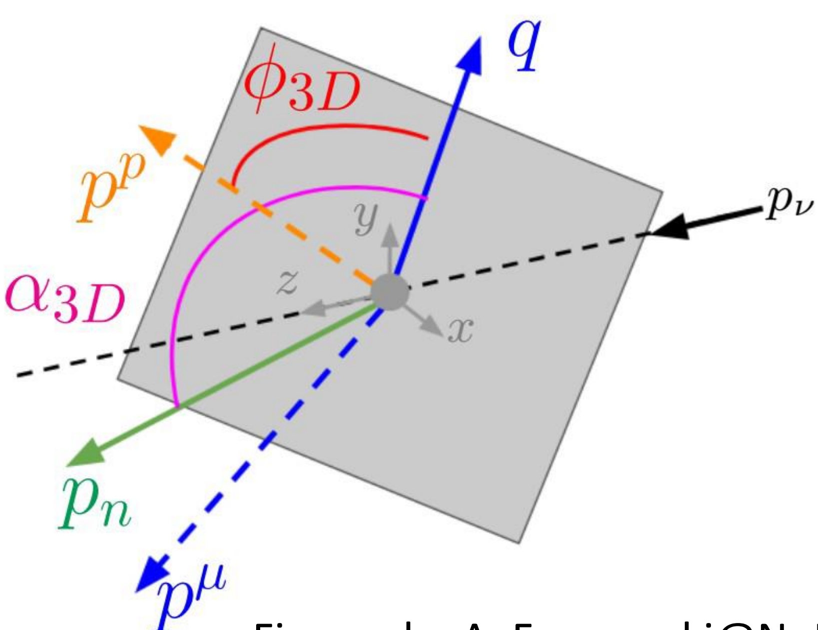
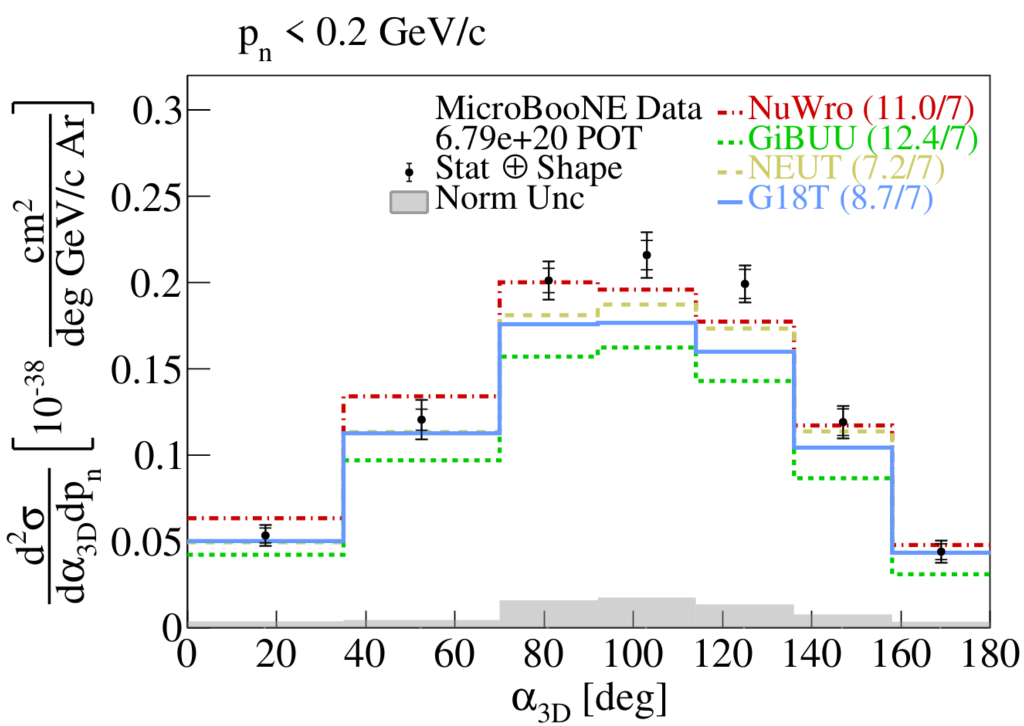
$$\alpha_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_n}{|\vec{q}||\vec{p}_n|}\right).$$

Select CCQE like events

α_{3D} for small missing momentum





Figures by A. Furmanski@NuINT24

Charged current quasi-elastic scattering

1) Nuclear modeling (binding effects)

Study @ MicroBooNE

arXiv:2310.06082

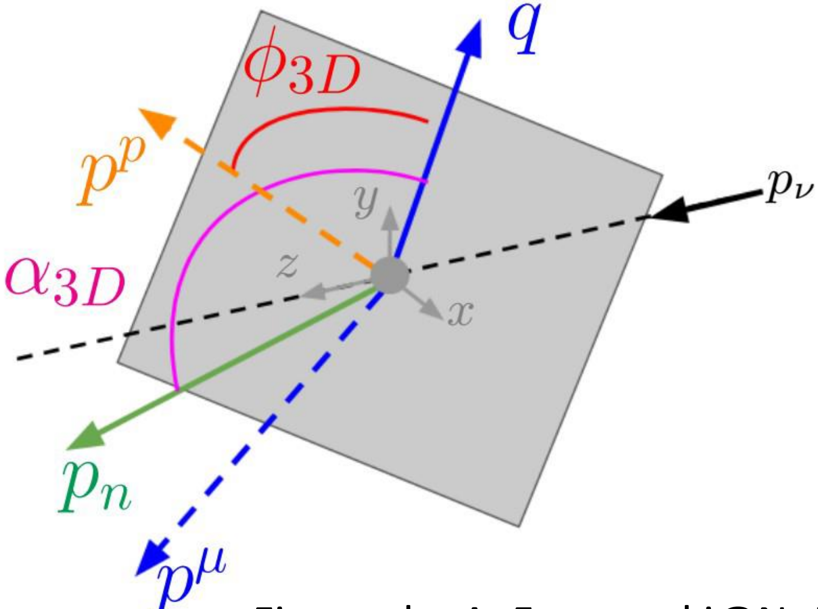
$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2},$$

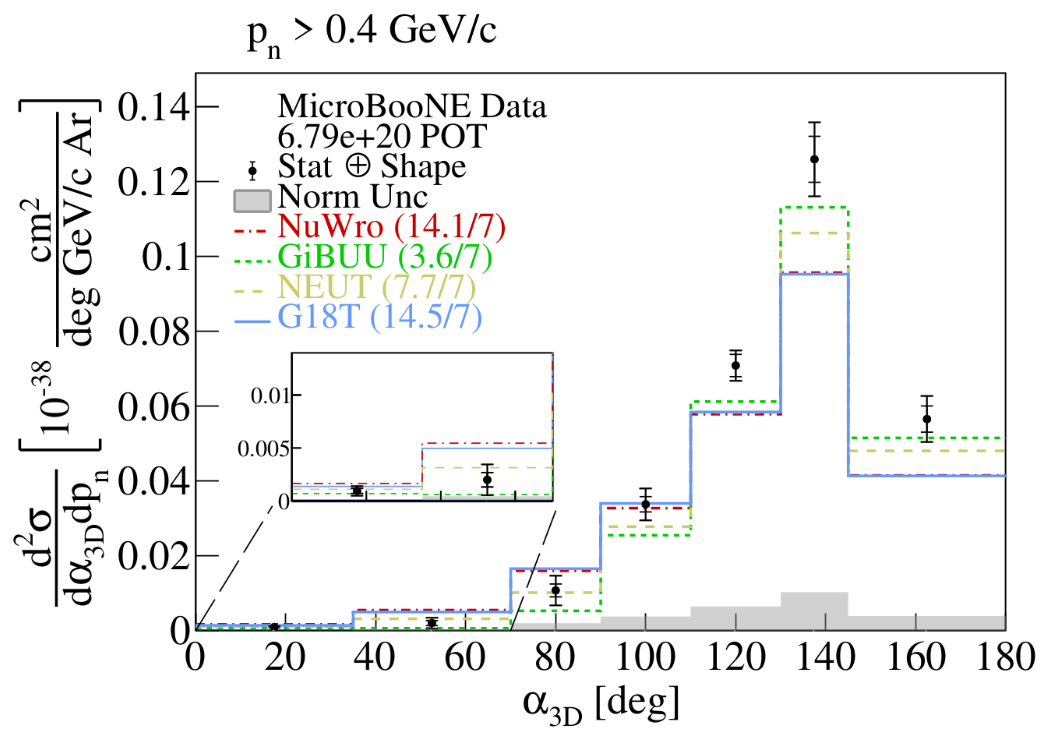
$$\phi_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_p}{|\vec{q}||\vec{p}_p|}\right),$$

$$\alpha_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_n}{|\vec{q}||\vec{p}_n|}\right).$$

Select CCQE like events

α_{3D} for large missing momentum



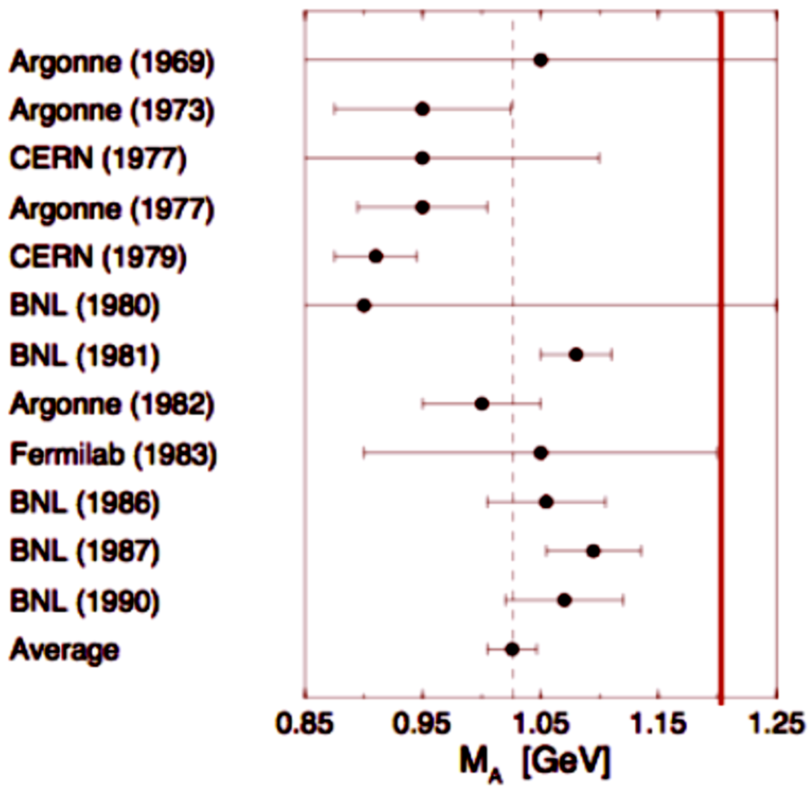


Figures by A. Furmanski@NuINT24

Charged current quasi-elastic scattering

2) Neutrino-nucleon interaction modeling

Axial vector form factor (dipole) $F_A(q^2) = -\frac{1.276}{(1-(q^2/M_A{}^2))^2}$



Experiment	Target	Cut in Q^2 [GeV^2]	$M_A[GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

M_A was ~1.0 GeV/c^2 from experiments in 1970s and 1980s (most of them were bubble chamber experiments).

However, M_A is larger in most of the experiments after 1990s.

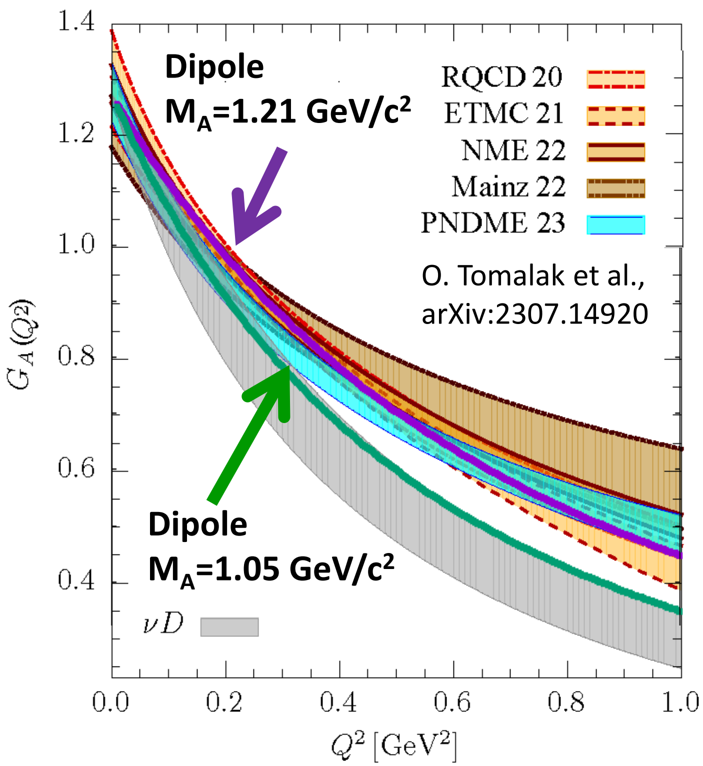
Charged current quasi-elastic scattering

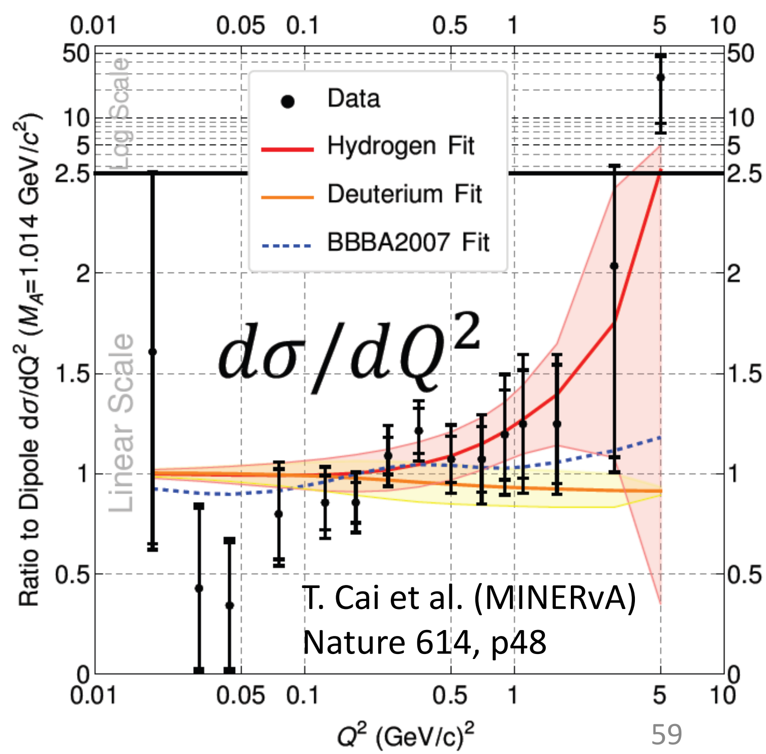
2) Neutrino-nucleon interaction modeling

Axial vector form factor (dipole) $F_A(q^2) = -\frac{1.276}{(1-(q^2/M_A{}^2))^2}$

Recent lattice QCD (LQCD) results suggest the larger M_A from bubble chamber data fit and non-dipole.

MINERvA measured ds/dQ^2 of $\overline{\nu_\mu}\,\mathrm{p} \to \mu^+\mathrm{n}$ scattering. Enhance in the large Q^2.

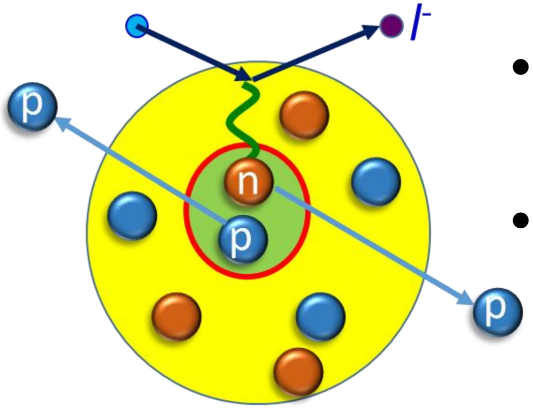




Charged current quasi-elastic-like events

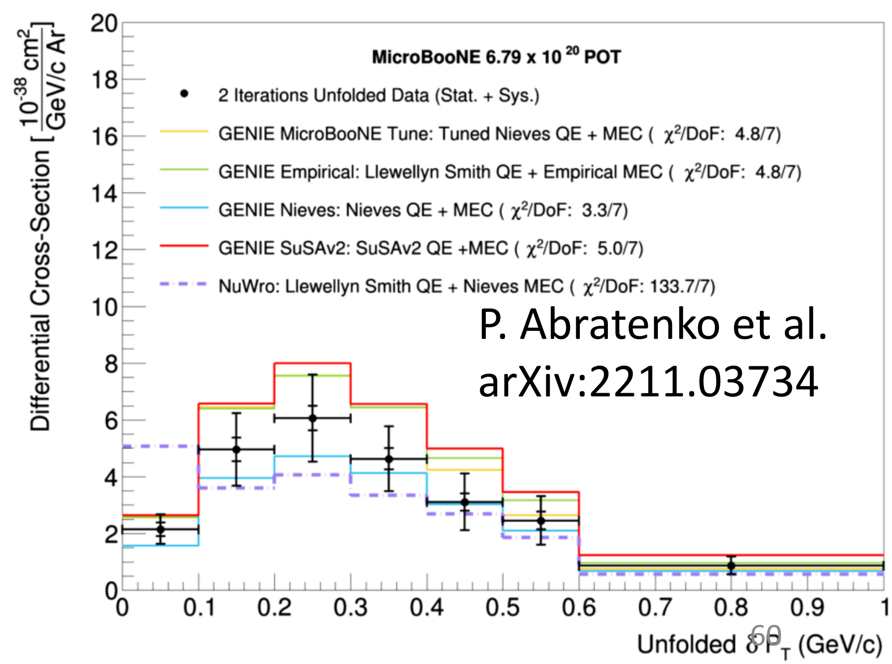
3) "CCQE-like" interaction

"multi-nucleon" scattering $\nu\, N_1 N_2 \rightarrow l^{\pm}\, N_1' N_2'$



- Known to exist from the electron scattering experiments.
- Some models were proposed and implemented in simulation programs. (But it is difficult to implement models completely.)

- It has been difficult to "identify" this interaction experimentally.
- *New experiments (detectors) have started publishing results.*
  - MicroBooNE did the first differential cross-section measurement of 1 μ + 2 protons + 0 pion.



P. Abratenko et al.
arXiv:2211.03734

Charged current quasi-elastic-like scattering

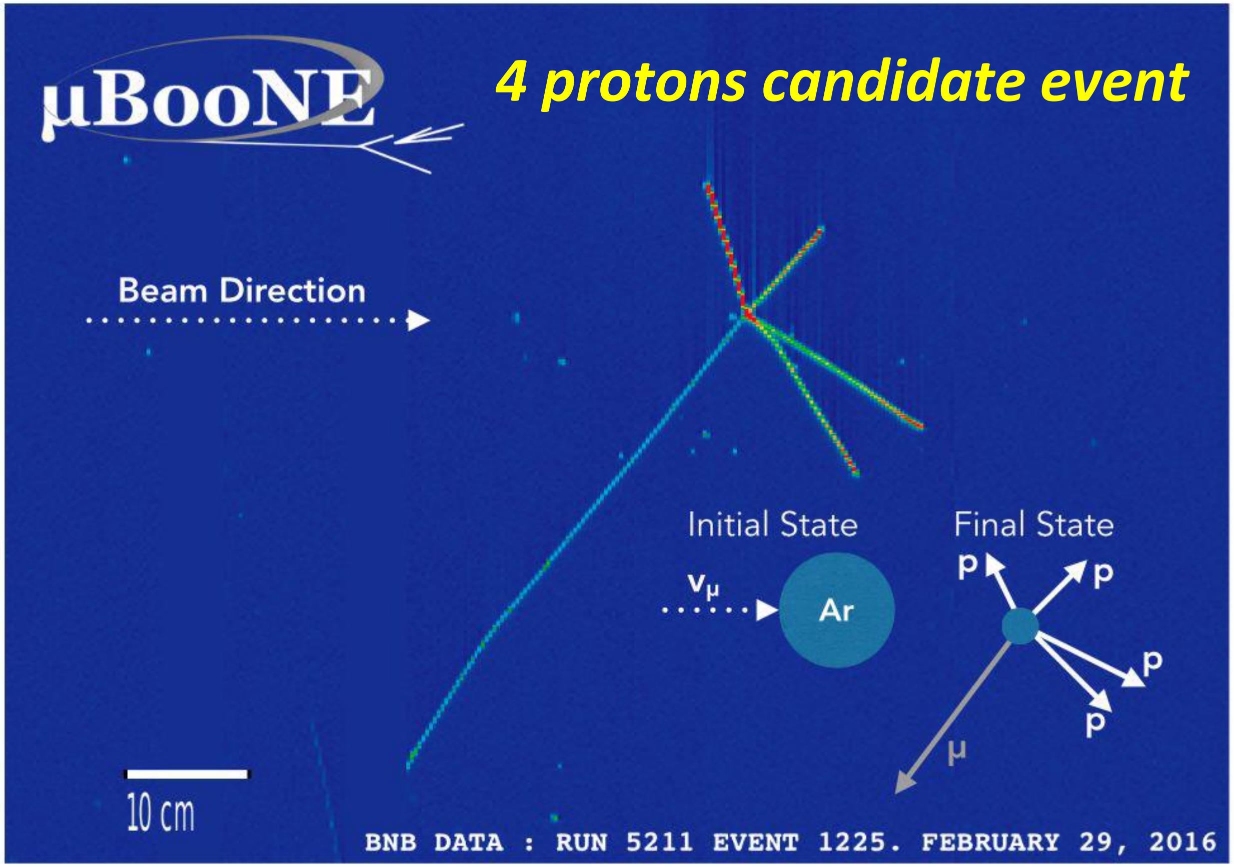
MicroBooNE (Lq. Ar TPC) https://arxiv.org/abs/2403.19574

Charged current 0π N protons ($N \geq 1$)

μ^- momentum from 0.10 to 1.2 GeV/c

Proton momentum from 0.25 to 1.0 GeV/c.

(This applies only to the leading proton)



Charged current quasi-elastic-like scattering

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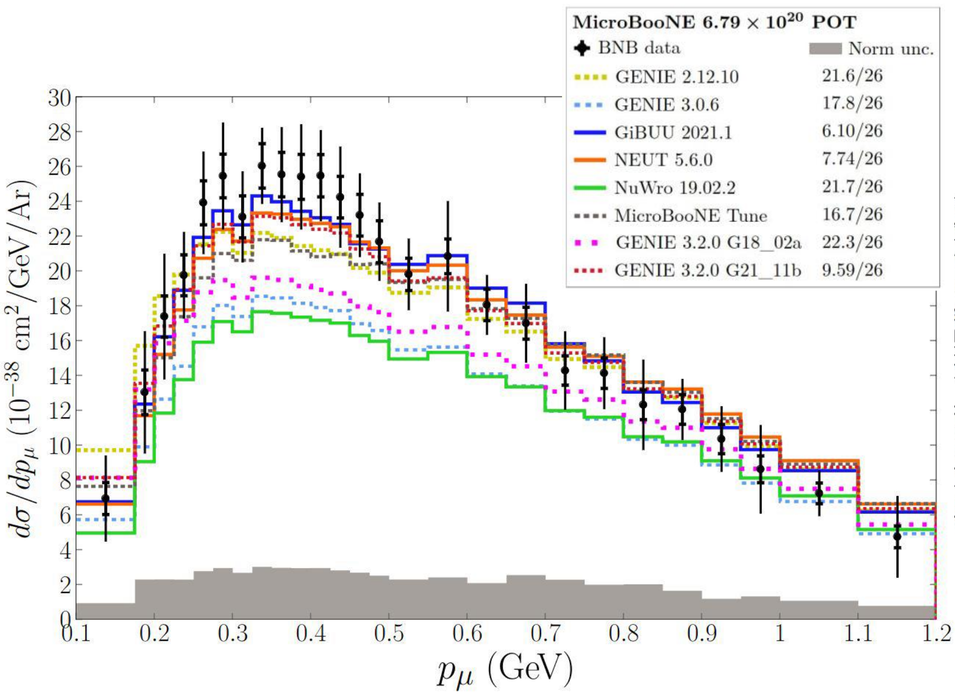
Charged current 0π N protons ($N \geq 1$)

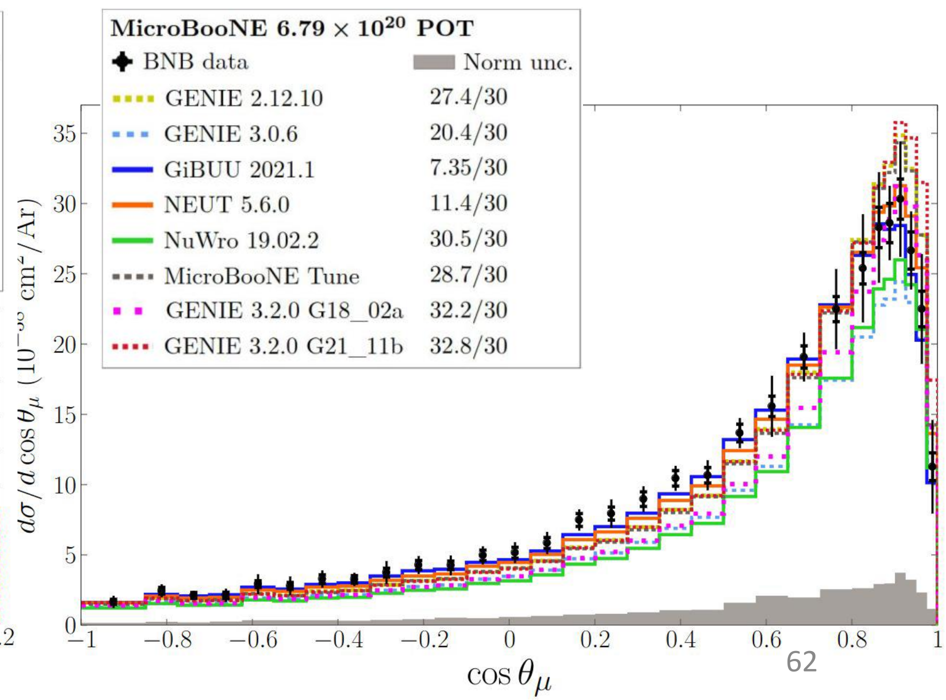
μ^- momentum from 0.10 to 1.2 GeV/c

Proton momentum from 0.25 to 1.0 GeV/c.

(This applies only to the leading proton)

Data prefer higher cross section in certain phase-space regions





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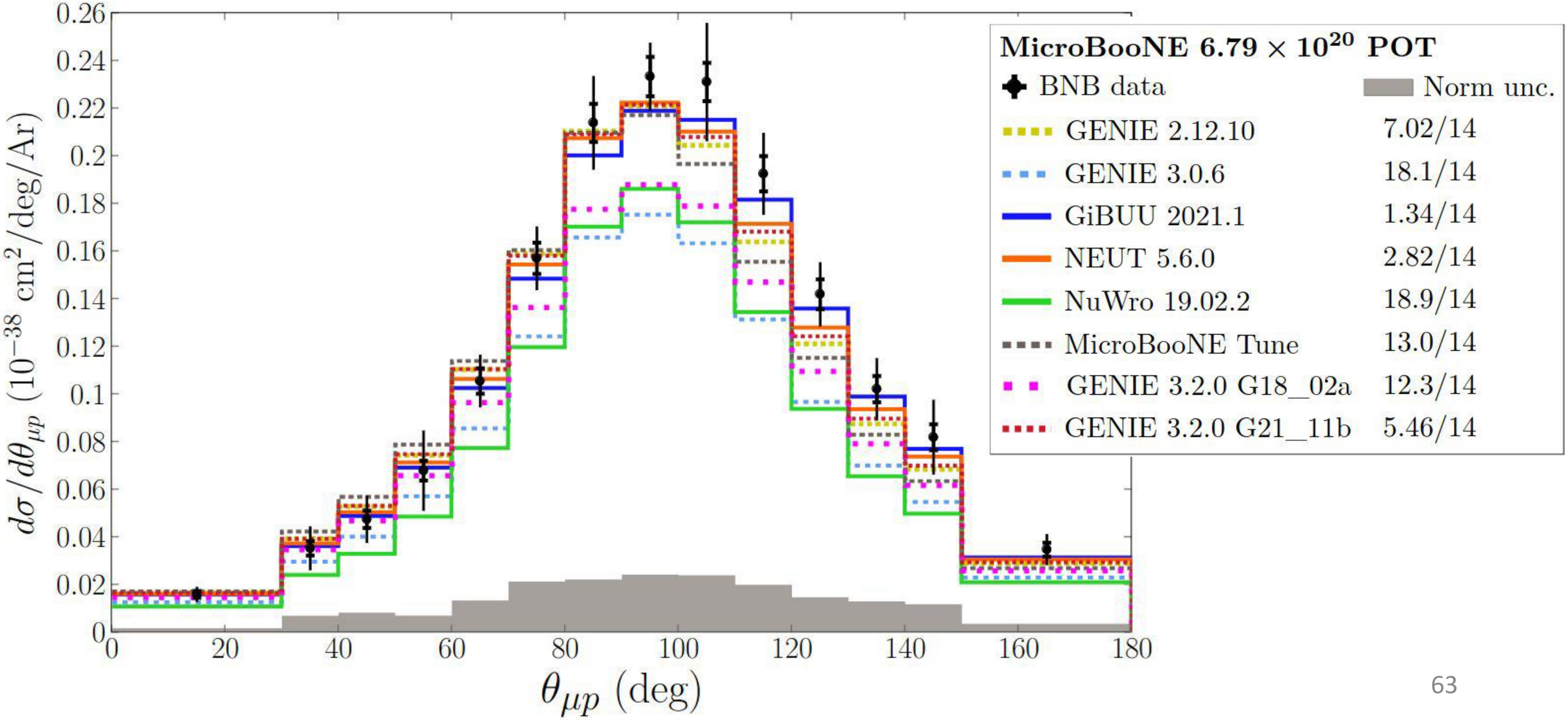
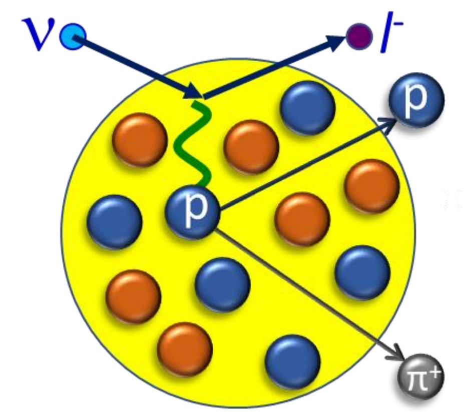


Single pion production

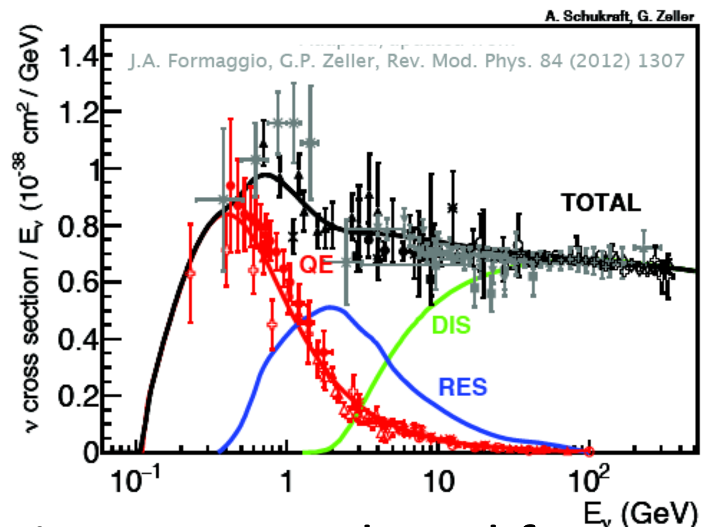
Charged and neutral single π production

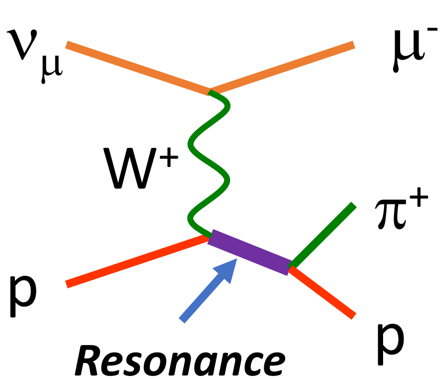
$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Dominant interaction around 1 to a few GeV.



- Dominant interaction in medium energy or wide band ν experiments, like NOvA and DUNE.
- Background when selecting “CCQE” as a signal, like T2K.
- Background of “proton decay” searches





- A large fraction of pions are produced from the decay of the intermediate resonance.
  Re-interaction probability of pion is large.
- Non-resonant contribution also exists.

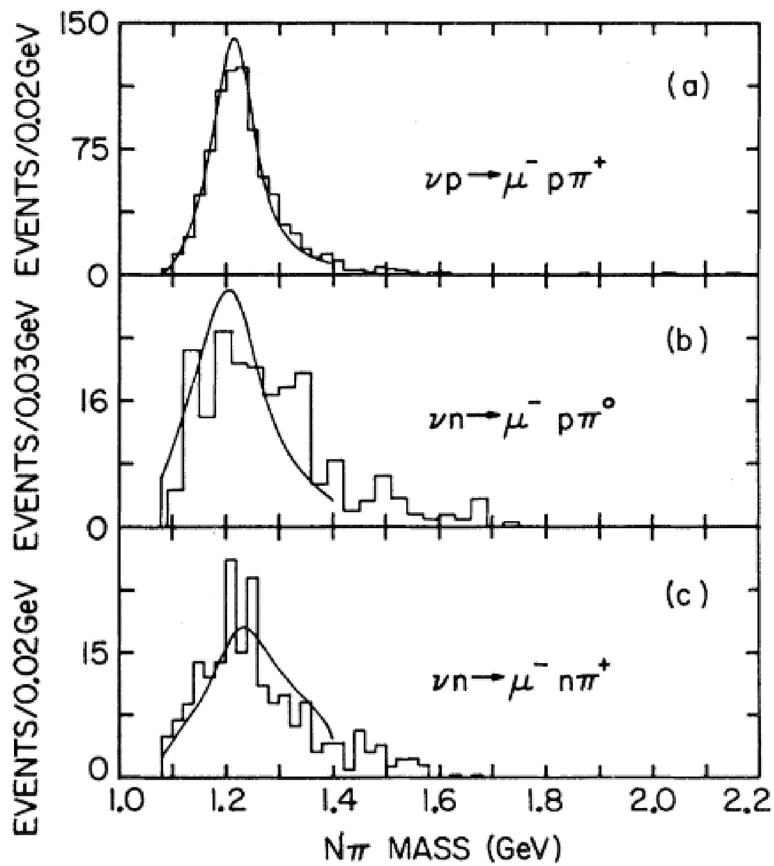
Complicated process

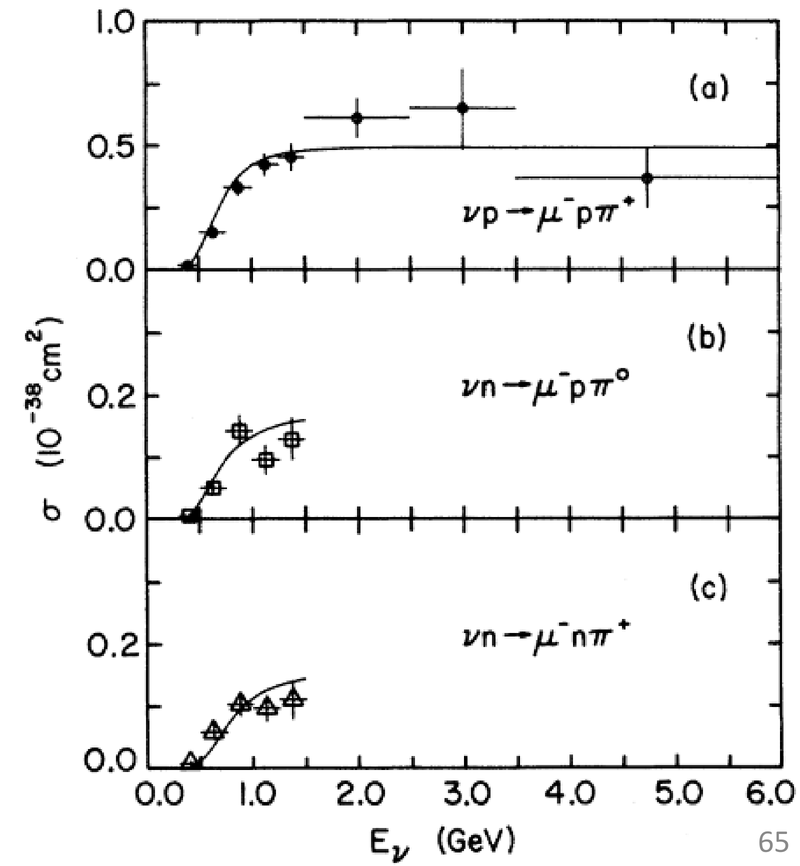
Single pion production

Charged and neutral single π production

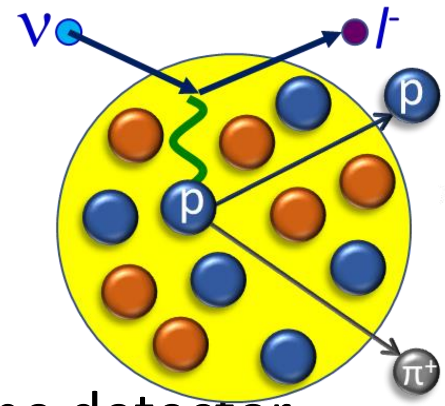
$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Bubble chamber data (ANL, D_2 target) clearly show the peak of the Delta resonance. G. M. Radecky et al., Phys. Rev. D 25, 1161





Single pion production



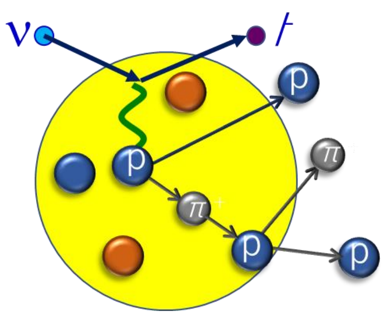
Charged and neutral single π production

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

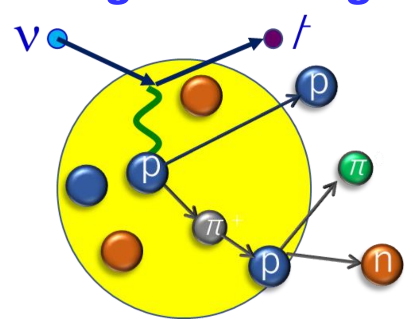
High probabilities of pion interactions

in the nucleus and secondary interaction in the detector

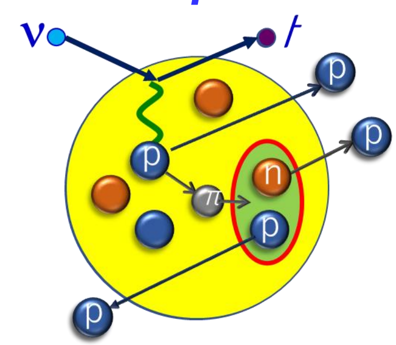
Inelastic scattering



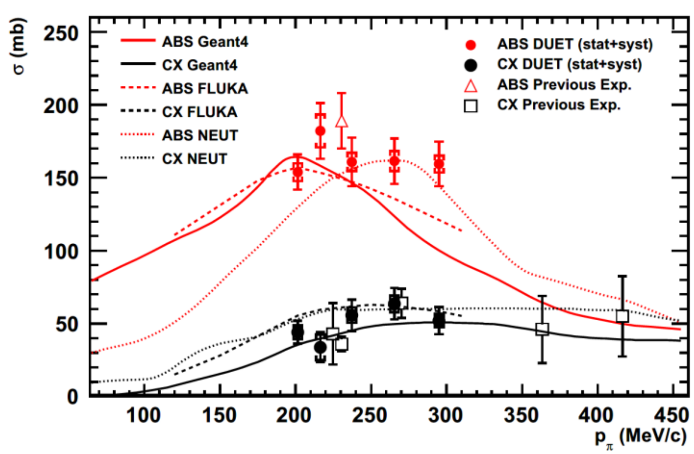
Charge Exchange



Absorption



(Additional pions may be produced.)



Available pion scattering data sets are limited.

Few data above Δ region

(p_{π} > 350 MeV/c).

Source of uncertainty.

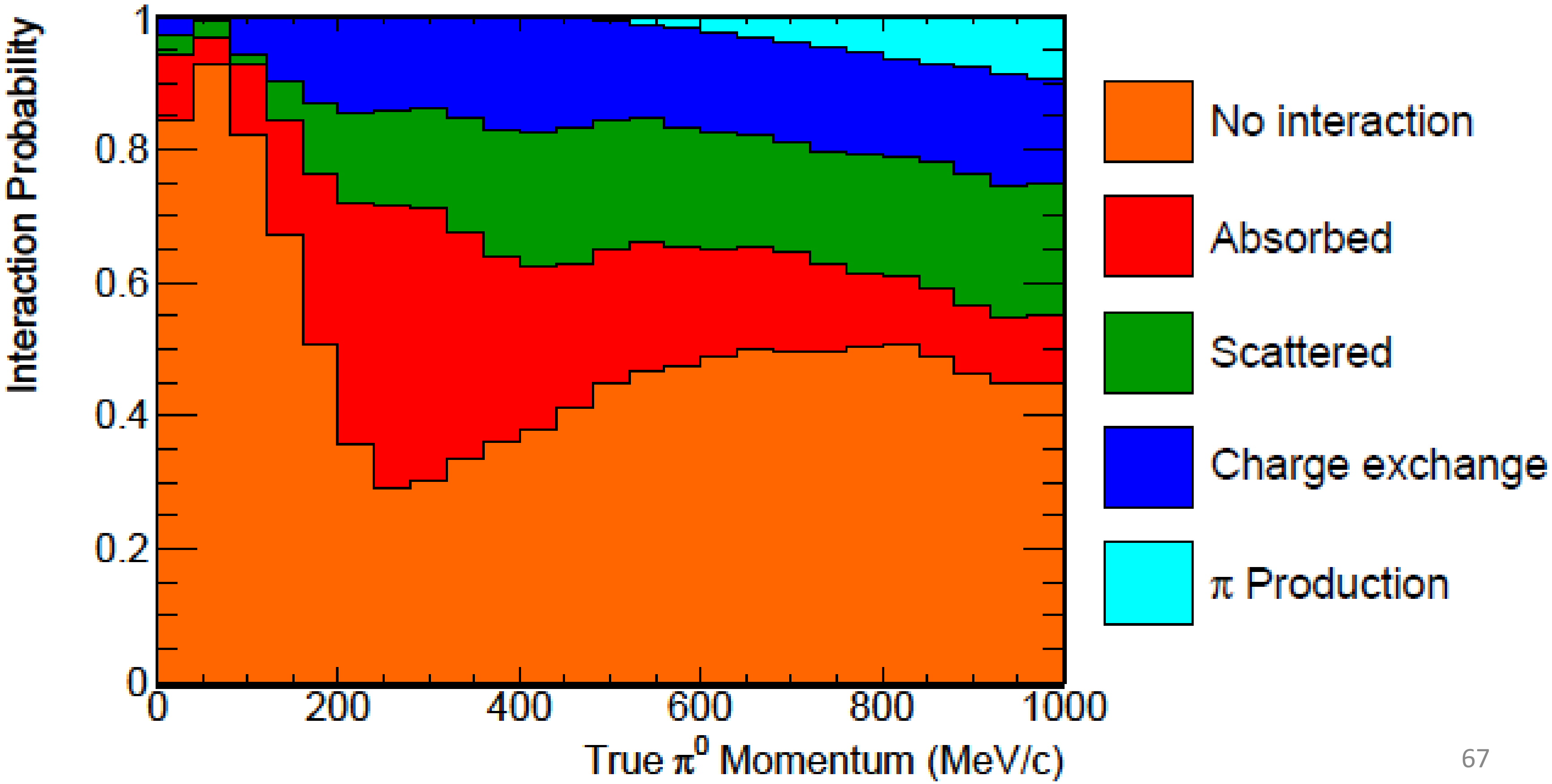
Single pion production

Interaction probability of pion in Oxygen nucleus

Large fraction of pions interacts or absorbed in the nucleus.

Events may be observed as “CCQE-like”, or

pion momentum and directions are measured differently.



Single pion production

T2K CC $1\pi^+$ measurement (Scintillator = CH target)

Select event with μ^- generated in the "Fine Grained Detector" (FGD) #1 and detected in the TPC #2.

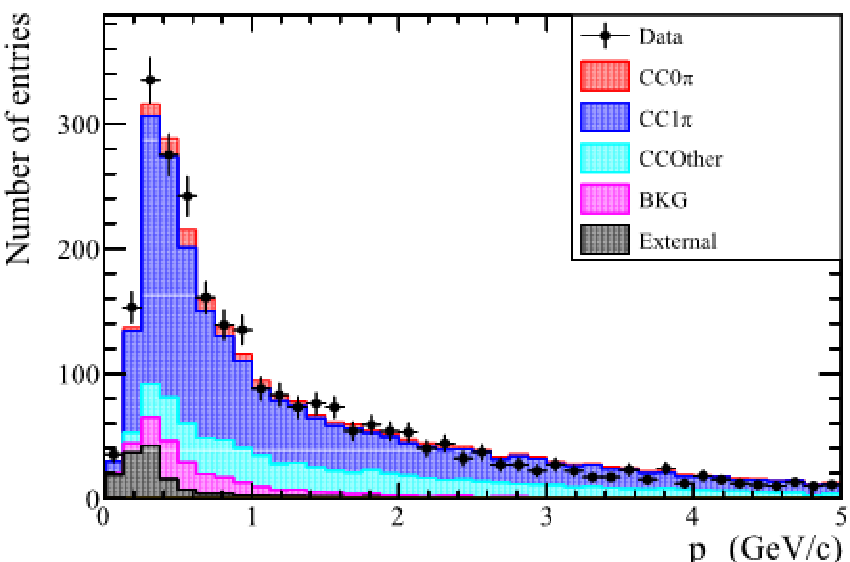
1 positively charged π^+ -like particle in TPC #2

or decay electron in upstream FGD fiducial volume.

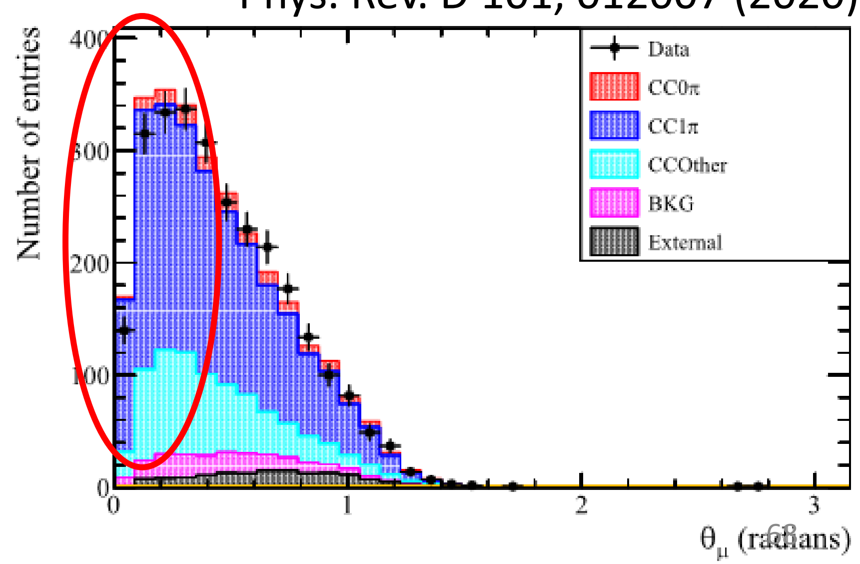
Purity = CC 1π production (primary interaction) is 61.5%.

Agreement of μ^- kinematics is quite well

but forward suppression seems to exist.



Phys. Rev. D 101, 012007 (2020)



Single pion production

T2K CC $1\pi^+$ measurement (Scintillator = CH target)

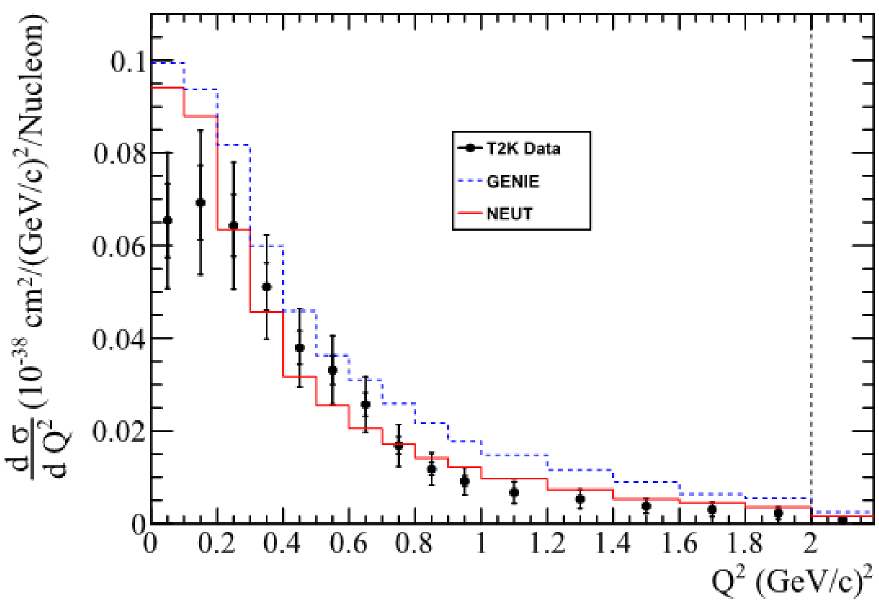
Suppression in the small q^2 seems to exist.

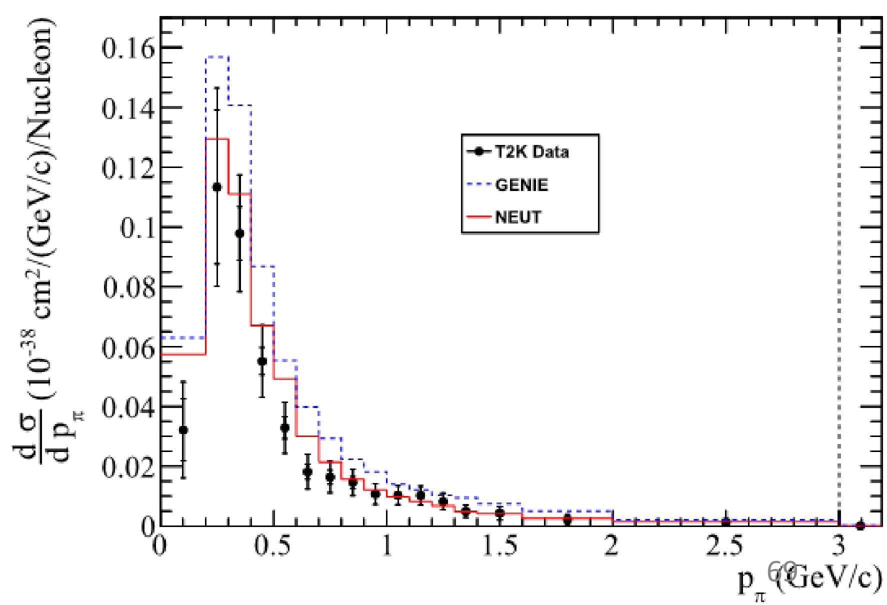
Cause of the forward angle μ^- discrepancy.

Agreement of π^- kinematics is worse than μ^-.

but forward suppression seems to exist.

Pion momentum distribution is largely affected by pion final state interactions in nucleus.

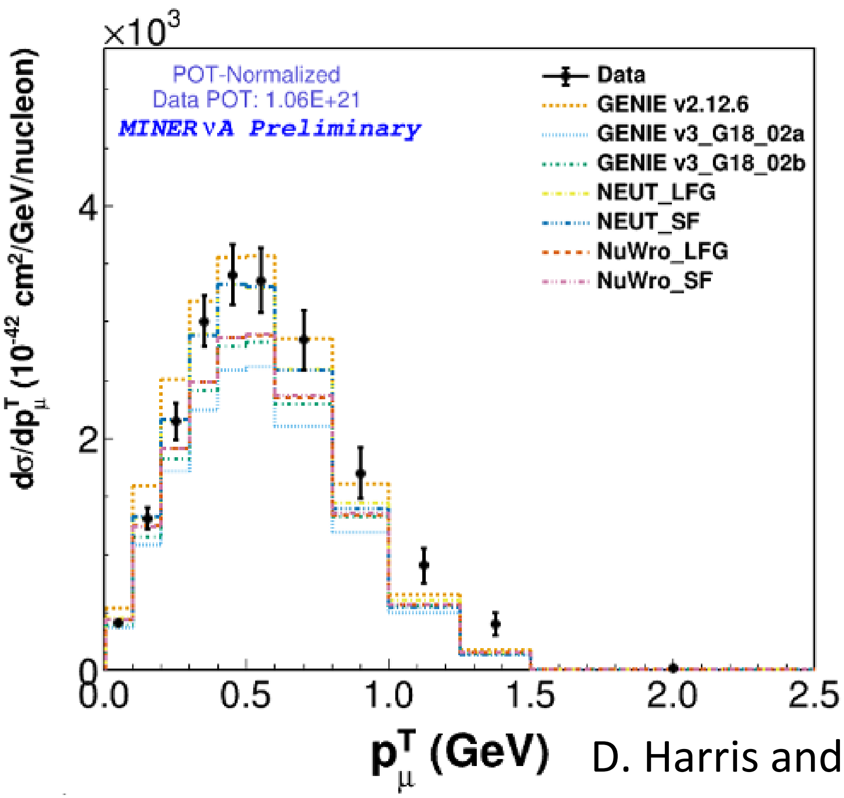


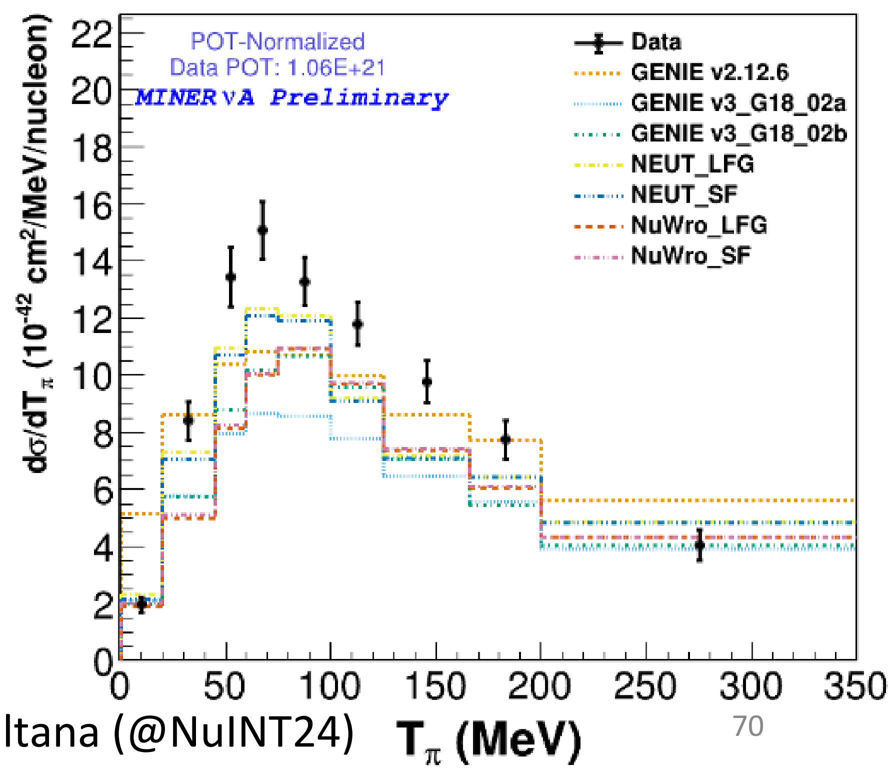


Single pion production

Charged single π^+ production from MINERνA

- Exactly one π^+ with any number of baryons
- Pion Kinetic Energy (T_π) between 0 and 350MeV
  (between 35 and 350MeV for θ_π result)
- Muon Angle w/rt beam: <20 degrees
- Muon momentum between 1.5 and 20 GeV/c



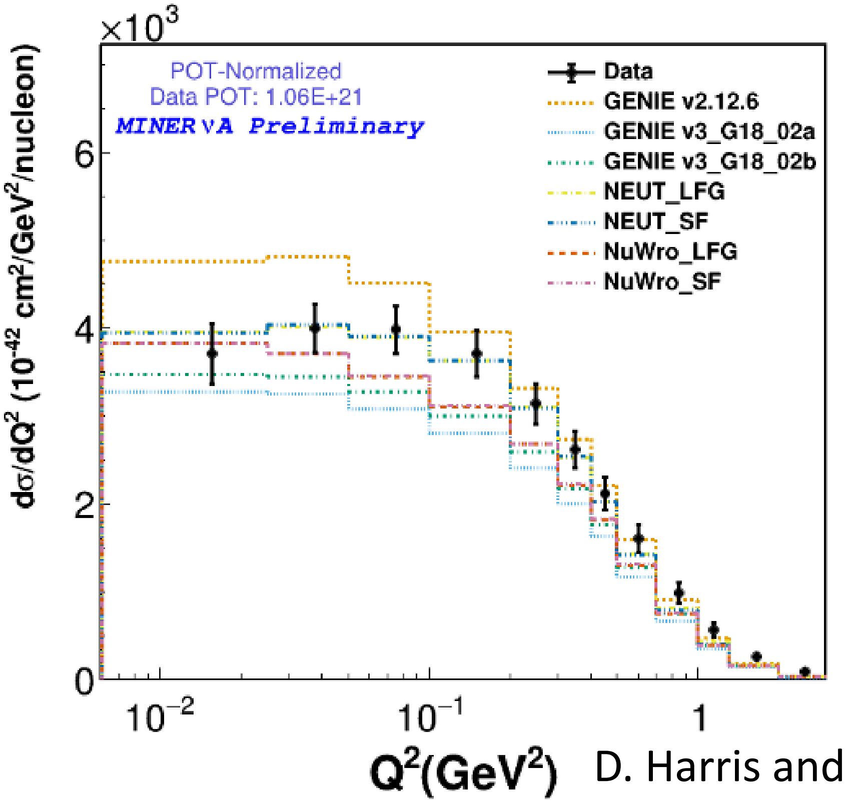


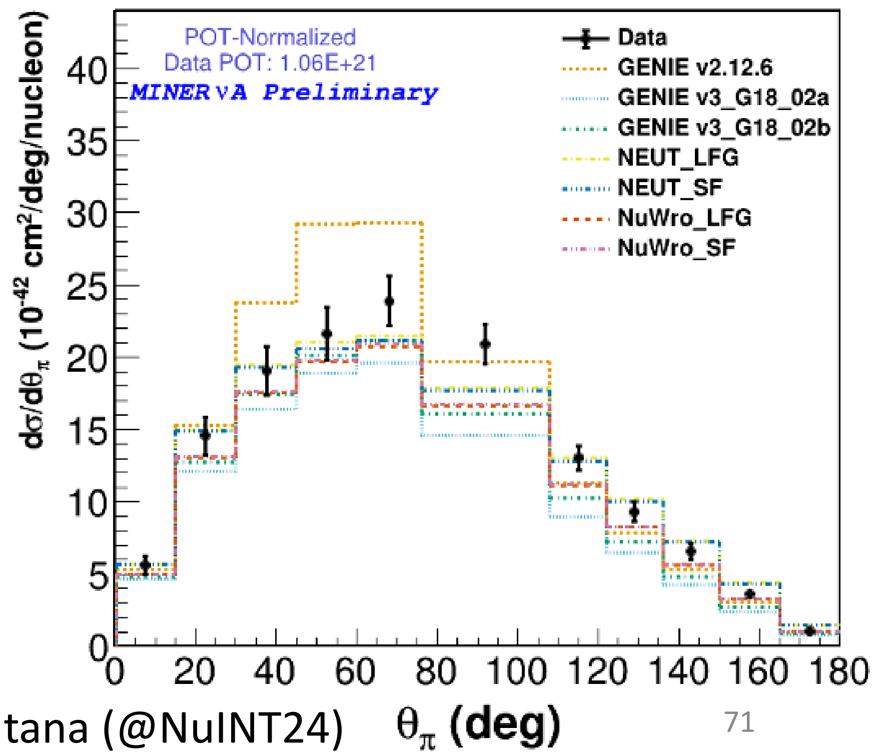
D. Harris and M. Sultana (@NuINT24)

Single pion production

Charged single π^+ production from MINERνA

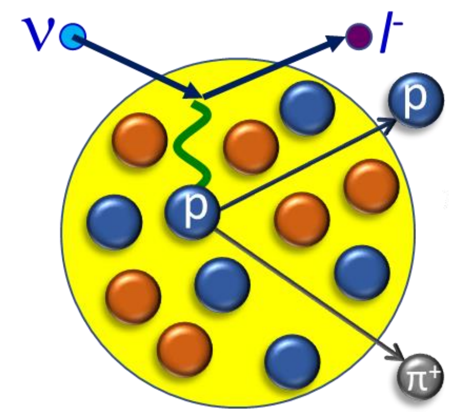
- Exactly one π^+ with any number of baryons
- Pion Kinetic Energy (T_π) between 0 and 350MeV
  (between 35 and 350MeV for θ_π result)
- Muon Angle w/rt beam: <20 degrees
- Muon momentum between 1.5 and 20 GeV/c





D. Harris and M. Sultana (@NuINT24)

Single pion production



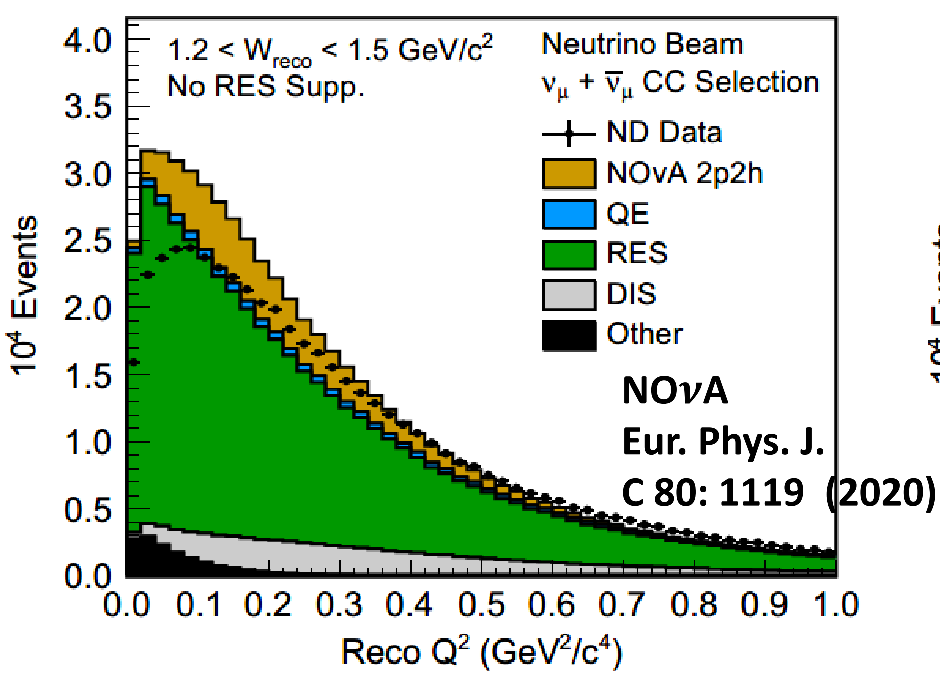
Charged and neutral single π production

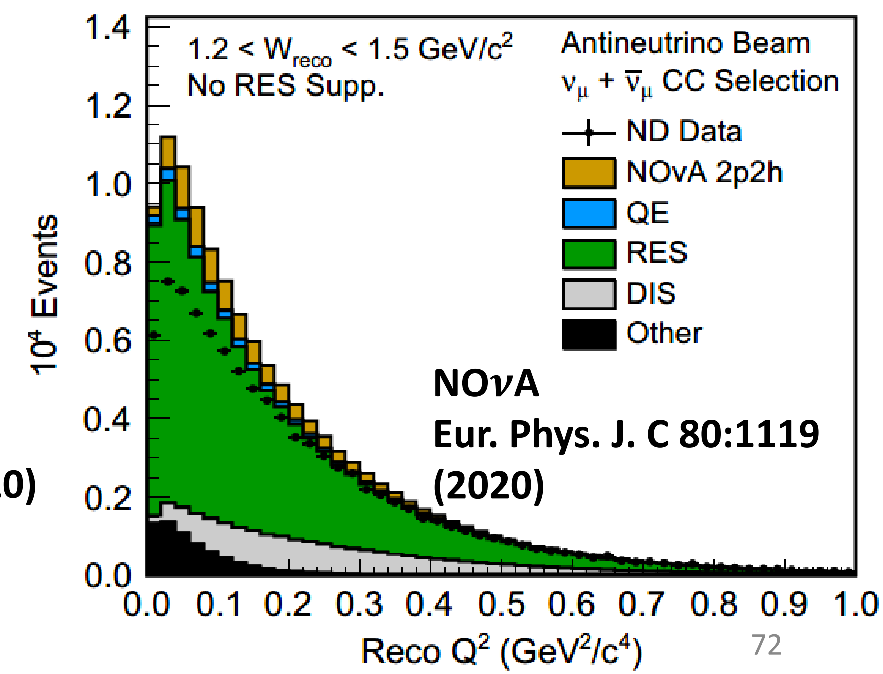
$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Discrepancies between the observation and simulation results

Suppression in small q^2 region.

(But predictions depend on the model.)



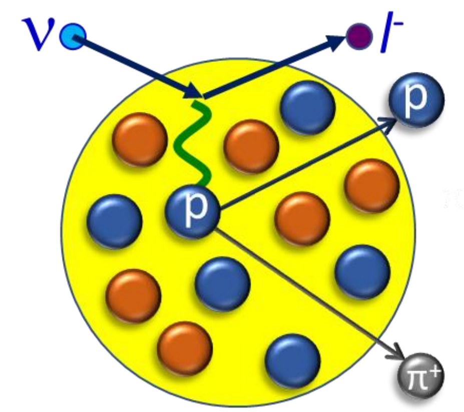


Single pion production

Charged and neutral single π production

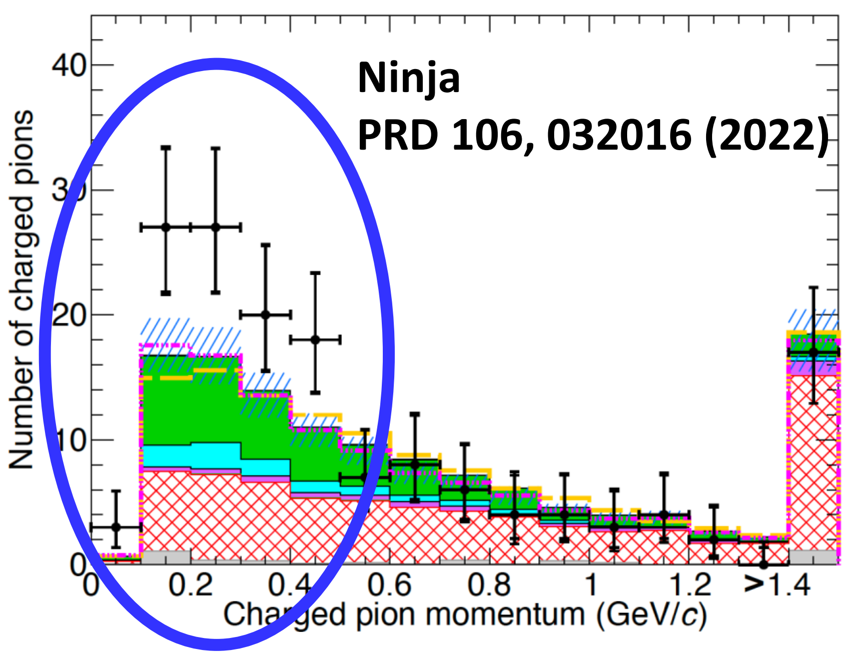
$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Discrepancies between the observation and simulation results

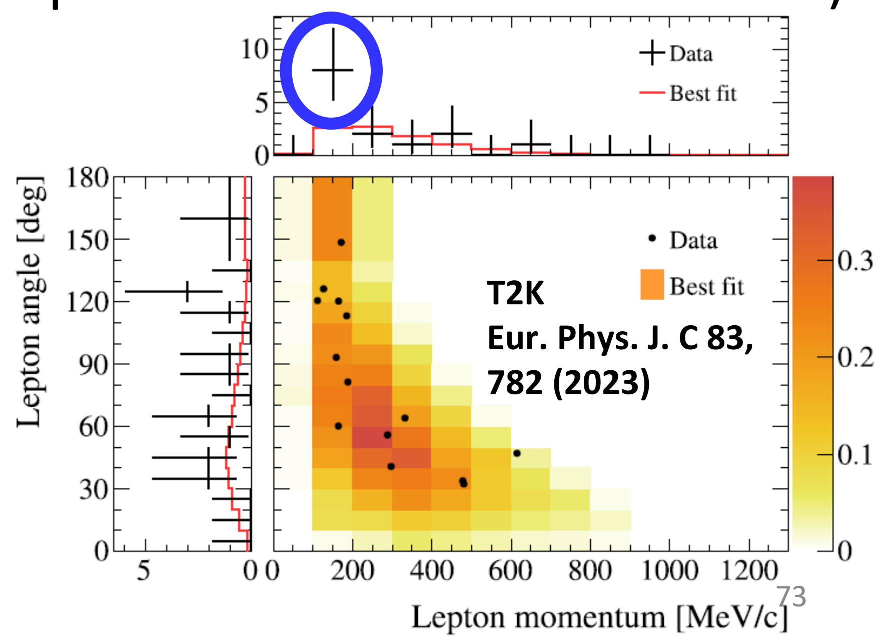


Low-momentum charged pion events excess in the data

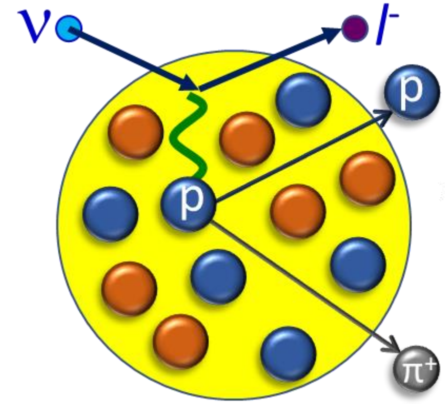
($\bar{\nu} + Fe$@Ninja)



Low-momentum lepton + pion events excess in the data (e-like 1 ring with decay-e@SK = pion momentum < therehsold)



Single pion production



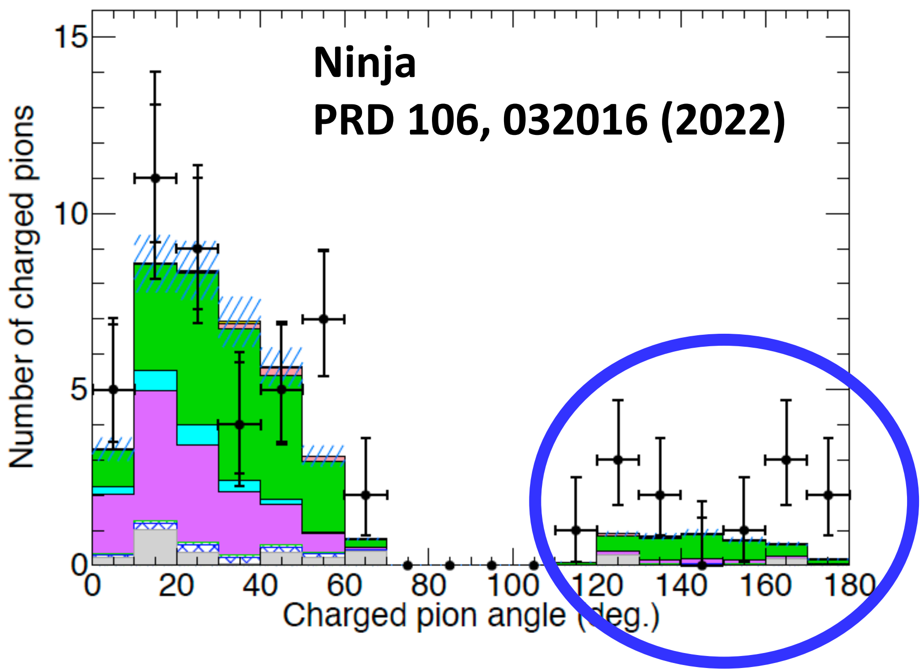
Charged and neutral single π production

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

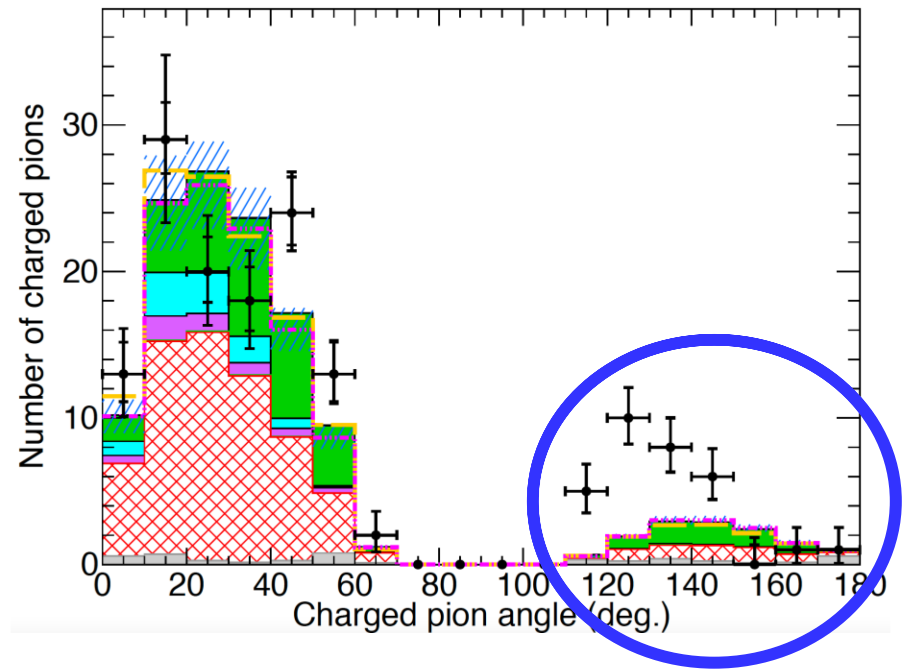
Discrepancies between the observation and simulation results

Larger # of charged pions in the backward direction.

($\nu + Fe$@Ninja)



($\bar{\nu} + Fe$@Ninja)

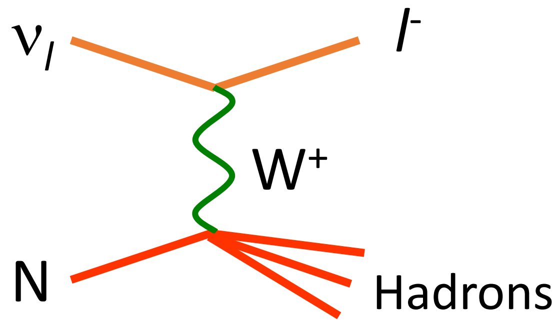


Shallow and Deep Inelastic scattering (SIS/DIS)

Charged and neutral SIS & DIS

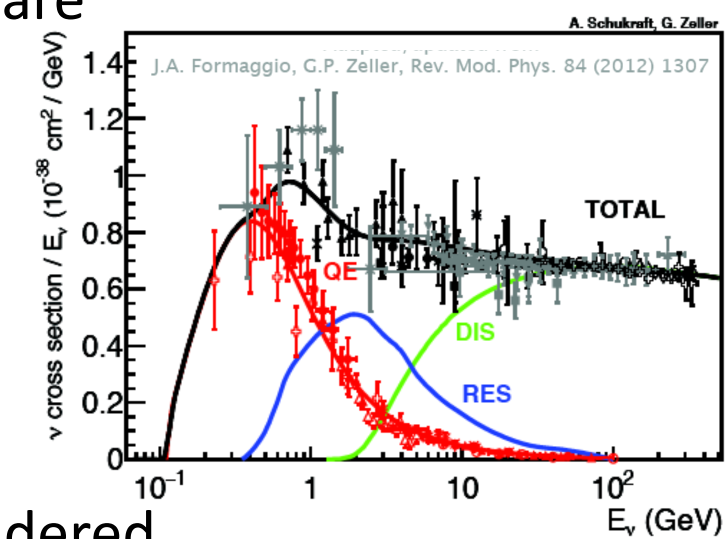
$$\nu + N \rightarrow l^{-}(\nu) + N' + X \ (X = hadrons)$$

Dominant interaction above a few GeV.



Described as neutrino-quark interactions.

- Rather simple cross-section equations with parton distribution functions.
- Parton distribution functions (PDF) are extracted from various high energy experiments.



Issues

Existing PDF does not cover the entire kinematic regions as-is. (Covers large q^2 and W regions.)

No nuclear dependences are considered.

➡ Careful treatments (corrections) are required to for the interactions from a few to 10 GeV.

Shallow and Deep Inelastic scattering (SIS/DIS)

Charged and neutral SIS & DIS

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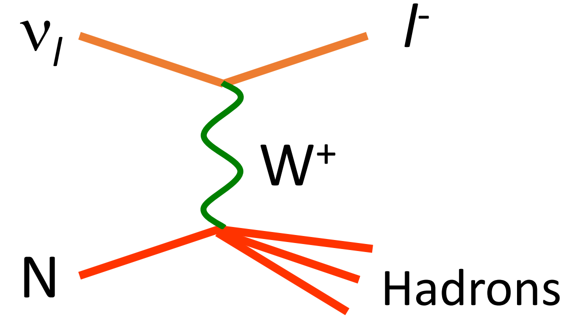
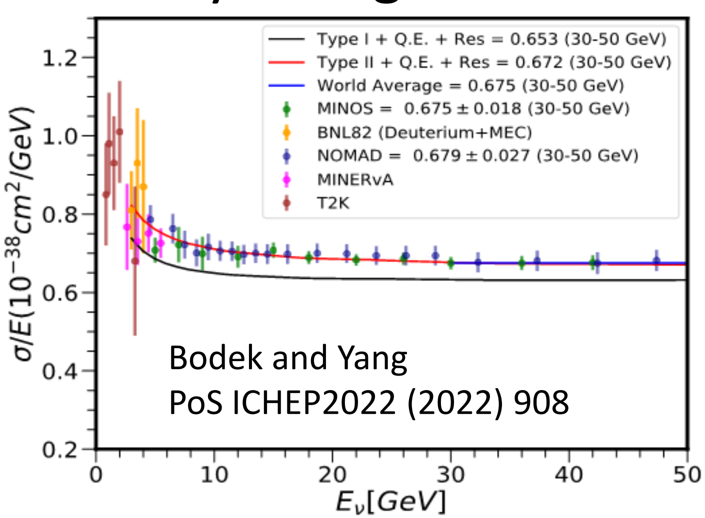
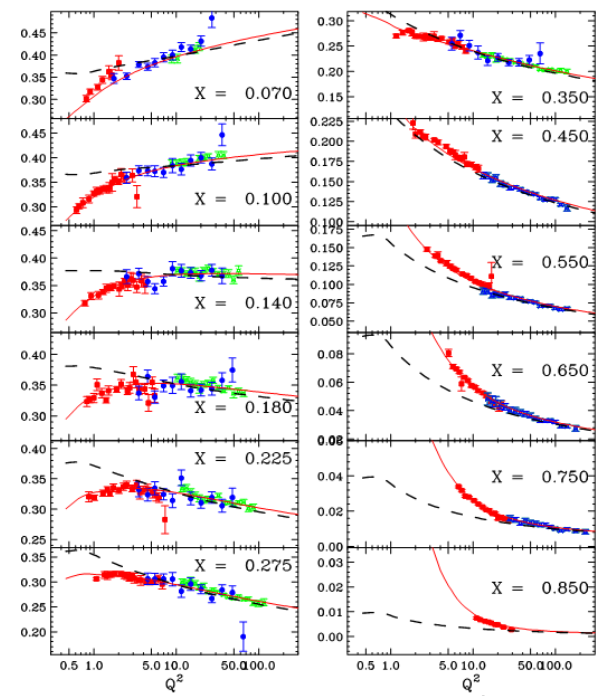


Model for "low energy" SIS / DIS

Prescriptions by Bodek and Yang are commonly used. Their model provide the way to extend the PDF to low q2, low W region. (Model parameters are extracted by fitting various data.)





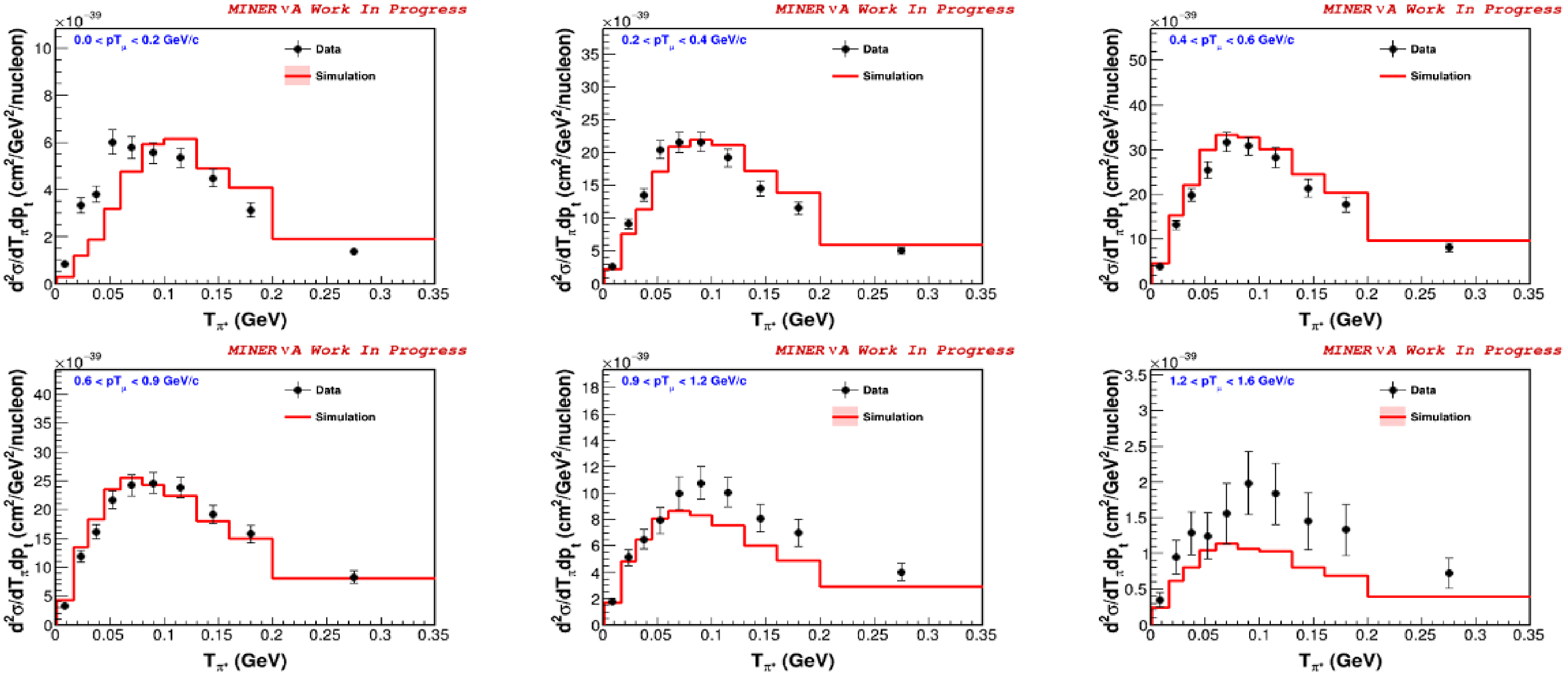
Bodek and Yang PoS ICHEP2022 (2022) 908

Pion productions (from single pion to SIS/DIS)

MINERνA is studying the events with 1 or more π^+.

Discrepancies in the pion momentum distribution.

Easily affected by re-interaction in the nucleus (FSI).



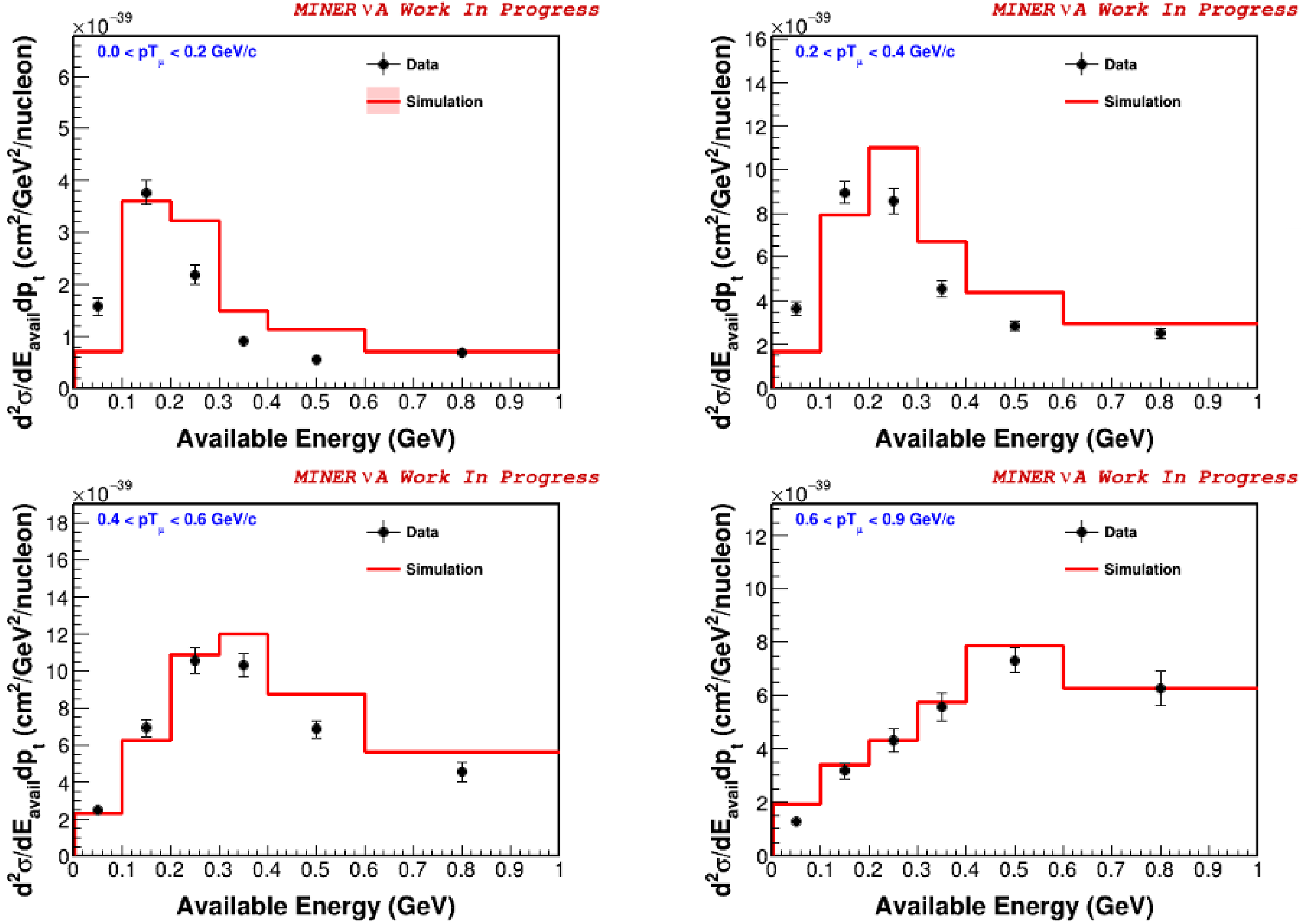
D. Harris and M. Sultana @ NuINT24

Pion productions (from single pion to SIS/DIS)

MINERνA is studying the events with 1 or more π^+.

$$E_{avail} = \sum T_p + \sum T_{\pi^{+/-}} + \sum E_{particles}$$

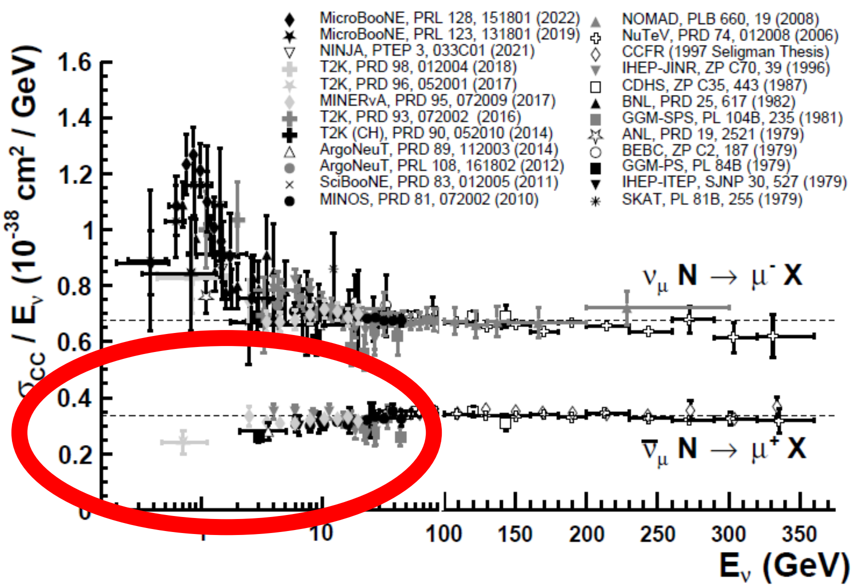
(Excluding neutrons)



$\overline{\nu_\mu}$ charged current inclusive cross-section measurement

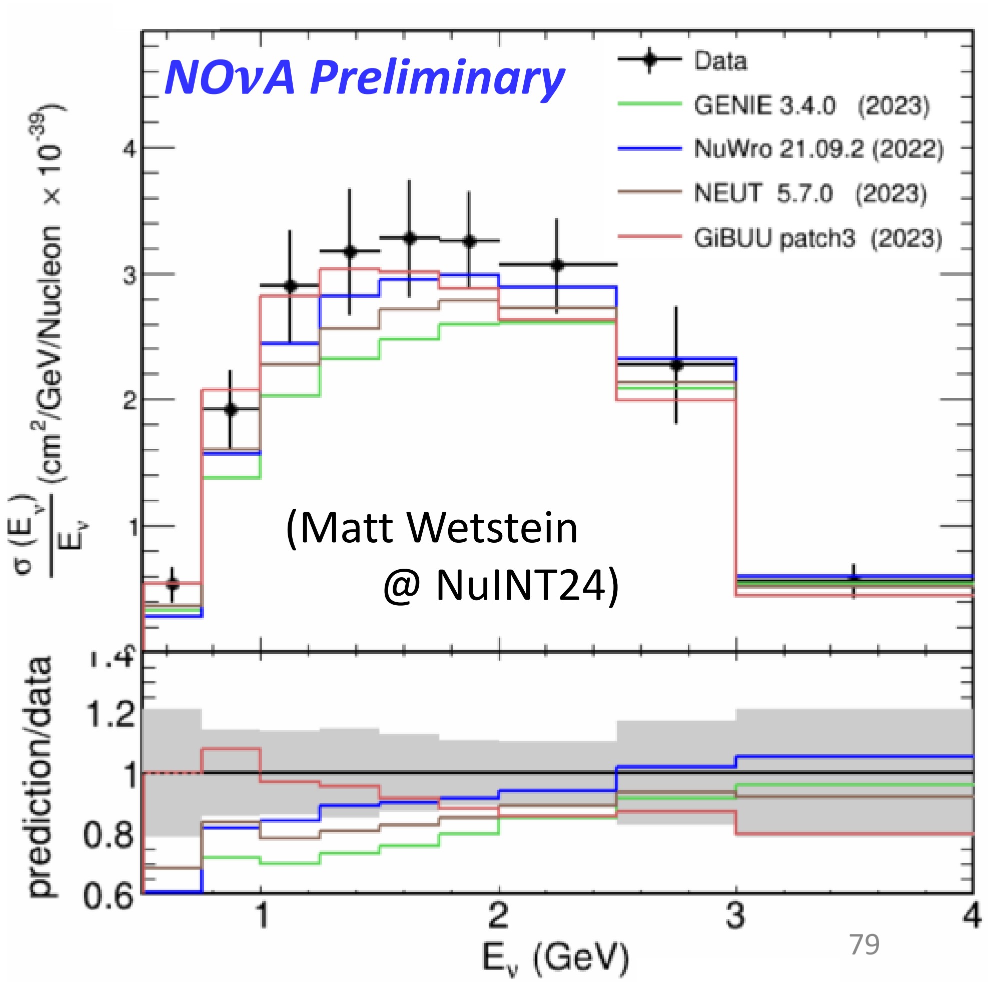
NOνA experiment recently reported the $\overline{\nu_\mu}$ charged current inclusive cross-section measurement from 0.5 GeV to 4 GeV.

Cross-section below 4 GeV has been poorly measured.



(G.P. Zeller's review)

S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)



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.
- Unfortunately, current our understanding turns out to be not precise enough to satisfy the requirements in the future experiments.
- There are various unsolved problems remaining even in the simplest quasi-elastic scattering ($\nu\, n \to l^-\, p, \bar{\nu}\, p \to l^+\, n$). More difficult situation for more complicated interactions, like single meson productions, shallow/deep inelastic scatterings and hadron re-interactions in the nucleus or in the detector.
- Existing and new neutrino scattering experiments will publish new results in coming years for further understanding.

Fin.