NEUTRINO CROSS-SECTION MEASUREMENT

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INO.

Plan of The Talk:

- Motivation.
- Neutrino interactions and cross sections.
- Different Experiments to measure neutrino cross sections
  - Descriptions.
  - Results.
- Conclusion.

Motivation:

- *To study nucleon structure.*
- *To predict rates of signal and background events for neutrino oscillation searches.*

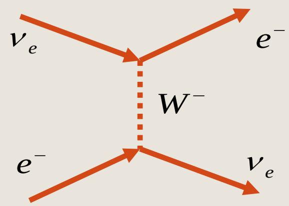
Neutrino Interactions :

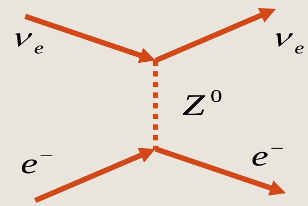
- Neutrino interacts only by weak interaction, by exchange of a gauge boson.
- Weak interactions are less probable to take place compared to other interactions, as the masses of W and Z bosons are large.(W~80GeV, Z~91GeV).
- These interactions are of two types: charged current interaction(CC) and neutral current interaction(NC).
- CC interaction is mediated by a W boson. A neutrino interacting with a nucleon exchange charge with the nucleon and turn into charged leptons.
- NC interaction is mediated by a Z boson.
- For both the interactions, several processes exist like elastic, pion production, deep inelastic scattering,coherent,resonant and diffractive.

Neutrino-electron interaction :

- For electron neutrinos the elastic scattering with electrons can be mediated by charged and neutral weak bosons (W and Z)

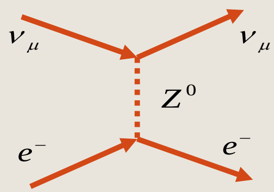
$$\nu_e + e^- \rightarrow \nu_e + e^-$$





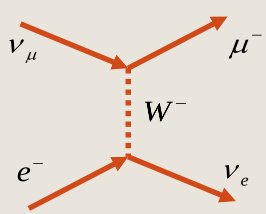
- The elastic scattering of muon and tau neutrinos from electrons is mediated only by the neutral boson.

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$



- The inelastic scattering processes are caused only by the charged currents.

$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



The cross section formulae for purely leptonic interactions:

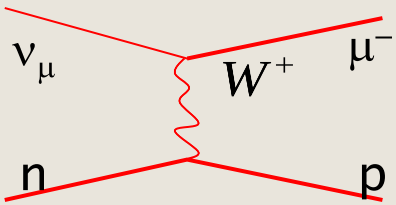
Elastic scattering	Inelastic scattering
$\sigma_{\nu_e e^- \to \nu_e e^-} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2+\frac{1}{3}\xi^2\right] \approx 9.5 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$	$\sigma_{\nu_\mu e^- \to \nu_e \mu^-} = \frac{G_F^2 s}{\pi} \approx 17 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$
$\sigma_{\bar\nu_e e^- \to \bar\nu_e e^-} = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2}+\xi\right)^2+\xi^2\right] \approx 4.0 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$	$\sigma_{\bar\nu_\mu e^- \to \bar\nu_e \mu^-} = \frac{G_F^2 s}{3\pi} \approx 5.7 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$
$\sigma_{\nu_\mu e^- \to \nu_\mu e^-} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2+\frac{1}{3}\xi^2\right] \approx 1.6 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$	For low energies, replace s by $(s-m_\mu^2)^2/s$.
$\sigma_{\bar\nu_\mu e^- \to \bar\nu_\mu e^-} = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2}-\xi\right)^2+\xi^2\right] \approx 1.3 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$	
$\xi = \sin^2\theta_W \approx 0.23$	

The cross section formulae for tau neutrinos are the same as for muon neutrinos.

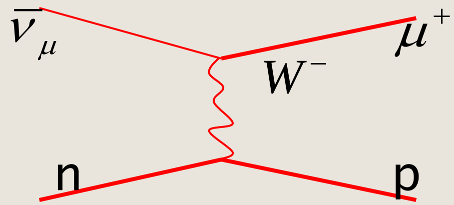
Ref. http://cupp.oulu.fi/neutrino/nd-cross.html

Neutrino-nucleon quasi-elastic scattering:

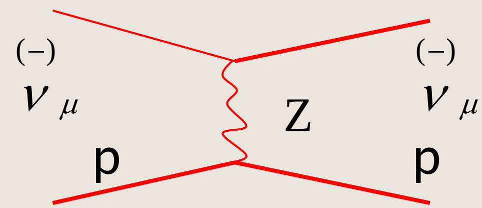
$$\nu_\mu + n \to \mu^- + p \qquad \bar{\nu}_\mu + p \to \mu^+ + n \qquad \overset{(-)}{\nu}_\mu + p \to \overset{(-)}{\nu}_\mu + p$$



CC



CC



NC

- Form factors introduced since proton, neutron not elementary.
- Depend on vector and axial weak charges of the proton and neutron.

Deep Inelastic neutrino-nucleon scattering:

- $\nu_\ell + N \rightarrow \ell + X$
- Parton model is used to make predictions for deep inelastic neutrino-nucleon scattering.
- Neutrino beams from pion and kaon decays, dominated by muon neutrinos are used to study this process.

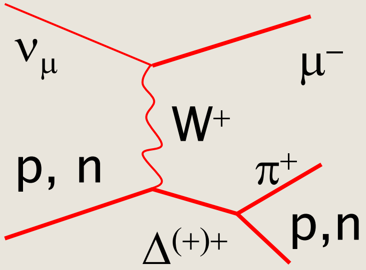
$$\nu_\mu + N \to \mu^- + X \qquad \overline{\nu_\mu} + N \to \mu^+ + X$$

- Since parity is not conserved in weak interactions, there are more structure functions for weak processes, like neutrino scattering, than for electromagnetic processes, like electron scattering.
- General form for the neutrino-nucleon deep inelastic scattering cross-section, neglecting lepton masses and corrections of the order of *M/E*:

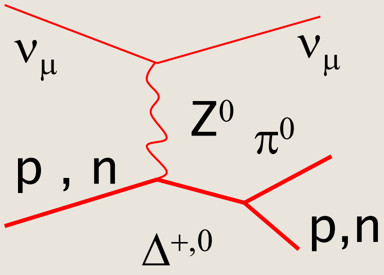
$$\frac{d\sigma_{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 ME}{\pi}\left[(1-y)F_2^{\nu,\bar{\nu}} + y^2 x F_1^{\nu,\bar{\nu}} \mp \left(y - \frac{y^2}{2}\right) x F_3^{\nu,\bar{\nu}}\right]$$

- The functions F_1 , F_2 and F_3 are the functions of Q^2 and ν. In the scaling limit they are the functions of x only.

Single pion production:



CC1π+



NC1π0

Neutrino-nucleon inelastic cross sections formulae:

For energies < 1 GeV :

Neutrino-nucleon	Antineutrino-nucleon
$\sigma_{\nu_e n \to e^- p} = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1 + \frac{Q}{E_\nu}\right)\sqrt{1 + 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}$	$\sigma_{\bar{\nu}_e p \to e^+ n} = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1 - \frac{Q}{E_\nu}\right)\sqrt{1 - 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E - Q)$
The vector and axial-vector coefficients have values g_V = 1 and g_A = 1.23. Hence the multiplier in the equations has the value $\frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2) = 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2$	

For very high energies (50 GeV < E < 250 GeV):

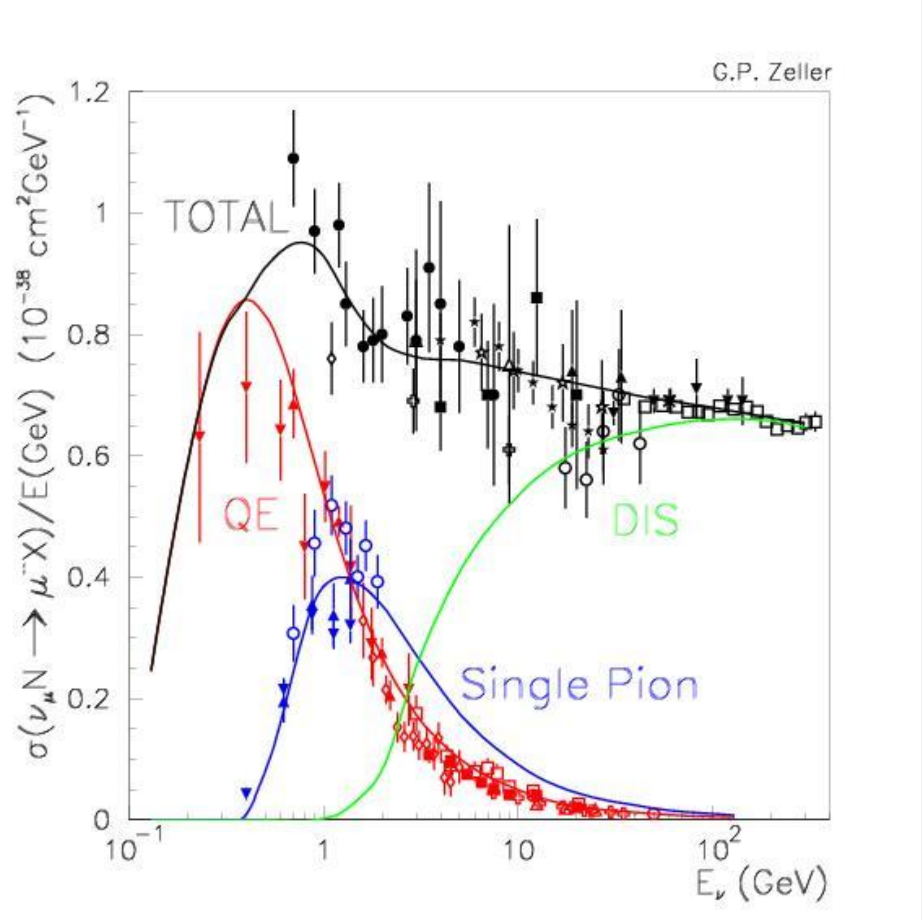
Neutrino-nucleon	Antineutrino-nucleon
$\sigma_{\nu_e N \to e^- X} \approx 6.7 \cdot 10^{-43} \left(\frac{E}{\mathrm{GeV}}\right) \mathrm{m}^2$	$\sigma_{\bar{\nu}_e N \to e^+ X} \approx 3.4 \cdot 10^{-43} \left(\frac{E}{\mathrm{GeV}}\right) \mathrm{m}^2$

Neutrino-nucleon elastic total cross sections formulae:

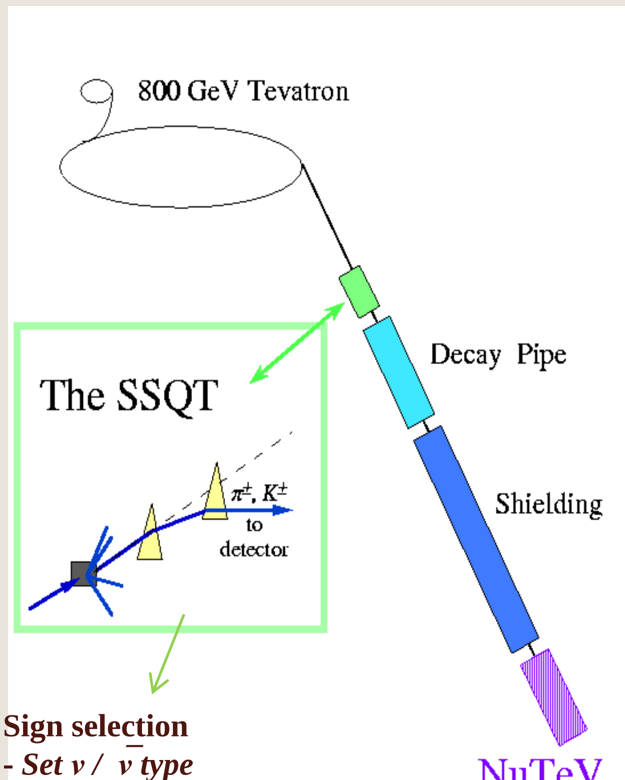
Neutrino-nucleon elastic c.s.
$\sigma_{\nu n \to \nu n}(E) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}\left(1 + 3g_A^2\right) \approx 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2.$
$\sigma_{\nu p \to \nu p}(E) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{4\pi}\left((16\xi^2 - 8\xi + 1)(1 + 3g_A^2\right) \approx 6.0 \cdot 10^{-50}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2.$

Ref. http://cupp.oulu.fi/neutrino/nd-cross.html

ν Cross Sections Picture :



NuTev (Neutrinos at the Tevatron):



Sign selection
- Set ν / $\bar{\nu}$ type
- Remove ν_e from K_{long}
(Bkgnd in previous exps.)

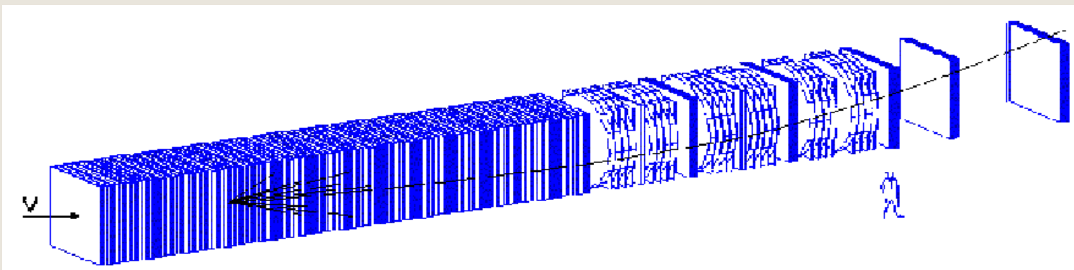
- It is a fixed target deep inelastic neutrino scattering experiment at Fermilab(1996-97).

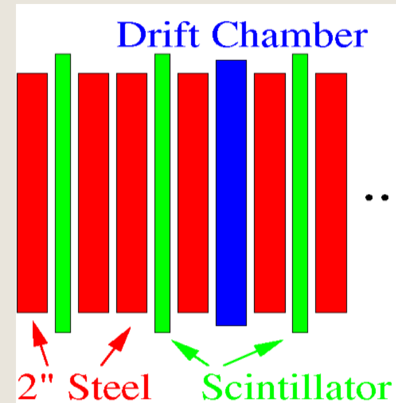
- Sign selected beamline.
- SSQT to produce a high purity neutrino or antineutrino beam.
- Decay pipe.
- Shield.

- Beam is almost pure ν or $\bar{\nu}$. (ν in $\bar{\nu}$ mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3}).
- Beam only has ~1.6% electron neutrinos.

- Uses a continuous calibration beam running concurrently with data taking.

NuTeV Detectors:

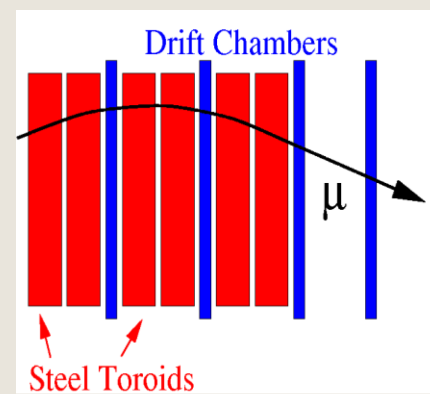




Target/Calorimeter:

- 168 Fe plates (3m×3m×5.1cm)
- 84 liquid scintillation counters

  (triggers the detector & measures visible energy, neutrino interaction point, event length.)
- 42 drift chambers.
- Solid Fe magnet → measures μ momentum/charge.
- Continuous Test Beam simultaneous with ν runs
  - Hadron , muon, electron beams
  - Toroid and calorimeter response are mapped.



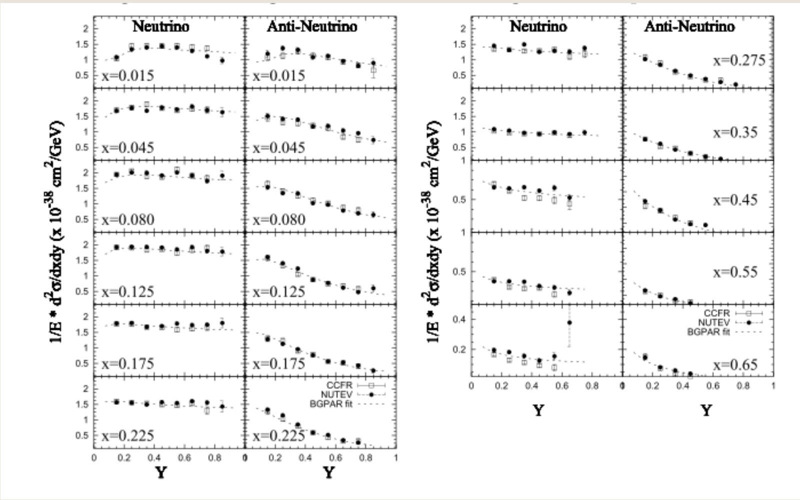
Toroid Spectrometer

Results:

- The differential cross section per nucleon ax a function of x , the Bjorken scaling variable, and y, the inelasticity , can be expressed in terms of the relative flux as function of energy and differential number of events as,

$$\frac{d^2\sigma^{\nu(\bar{\nu})}(E)}{dxdy} = \frac{1}{\Phi(E)} \frac{d^2N^{\nu(\bar{\nu})}(E)}{dxdy}$$

- Data selection criteria :
  a good muon track for accurate momentum measurement,
  minimum energy requirements :
  E_{Had}>10 GeV , E_μ>15 GeV, E_ν> 30 GeV.
- Neutrino Relative flux determined from a sample at low hadronic energy (< 20GeV) .As $y = \frac{E_{Had}}{E_\nu}$ →0 ,the integrated number of events are proportional to the flux.
- Detector simulation is used.

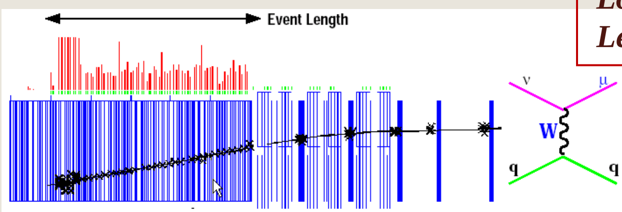


Differential cross sections for neutrinos and anti neutrinos at E_ν =85GeV (for diffferent x).

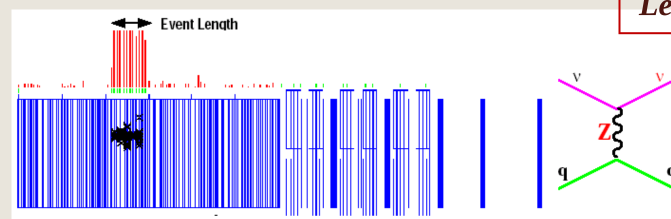
Measurement of Winberg angle:

- Also, this experiment measured the value of the Winberg angle utilising the Paschos-Wolfenstein Relation $$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right)$$
- NC/CC Event Separation :

CC Event: Long Event Length

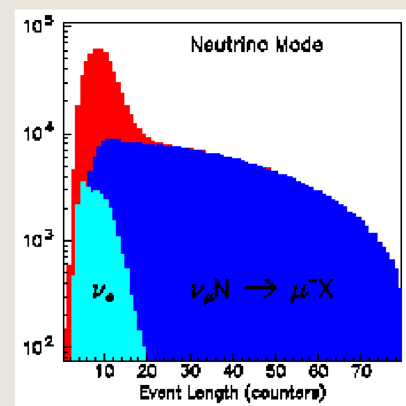


NC Event: Short Event Length



- ➢Statistical separation of NC and CC events
- ➢based on "Event Length"

$$R_{exp} = \frac{\text{Short events}}{\text{Long events}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$



The result!

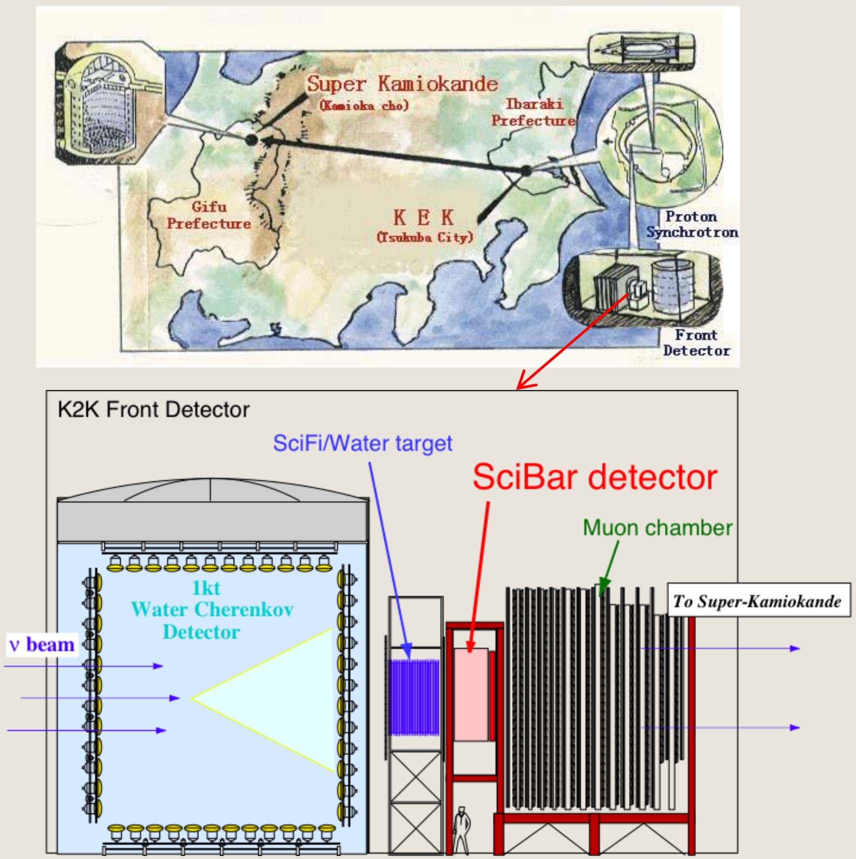
Measured value :

ν : 0.3916 ± 0.0007(stat)
$\bar{\nu}$: 0.4050 ±0.0016(stat)

$$\sin^2\theta_W = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

Gives a discrepancy of ~ 3σ!

K2K:

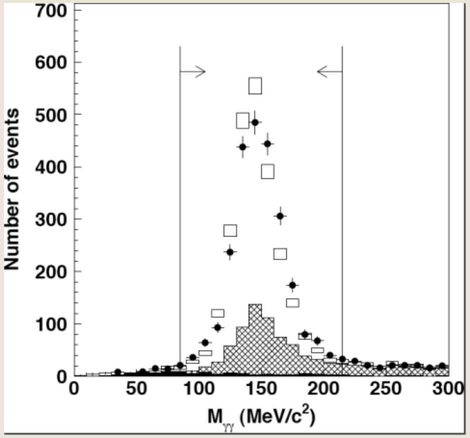


- Super-K as the far detector →to confirm atmospheric neutrino oscillations.
- Near detectors → to observe un-oscillated neutrinos and to measure neutrino cross sections.
- The K2K near detector ensemble→
  1 kton water cerenkov detector.
  A scintillating fiber water target tracker (SciFi).
  A solid scintillator tracker (SciBar).
  A muon range detector (MRD).
- 12 GeV protons on Al target at KEK→a ν_μ beam (97% purity)of peak energy 1.3 GeV.
- The first to publish updated neutrino cross section measurements in the 1 GeV range.

Results:

- Neutrino interactions on both carbon and oxygen-based targets was studied.

- 1 kt Water Cherenkov → Water target → The first measurement of NC π production in water.
- The ratio of neutral current single π^0
- production and the total CC cross section is calculated to be
- $\sigma_{NC1\pi0}/\sigma_{CC} = 0.063 \pm 0.001(stat) \pm 0.006(syst)$.
- This value agrees with the monte Carlo expectation of 0.064.

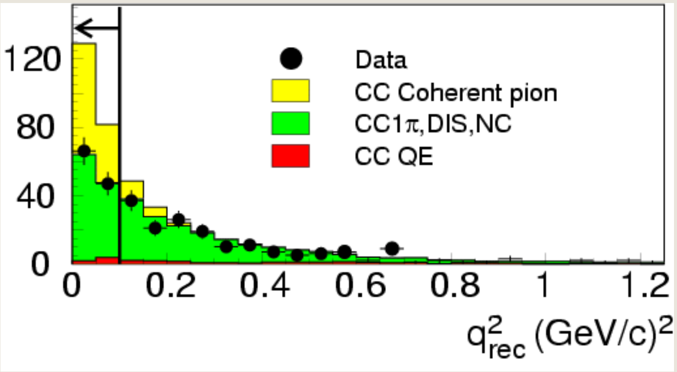


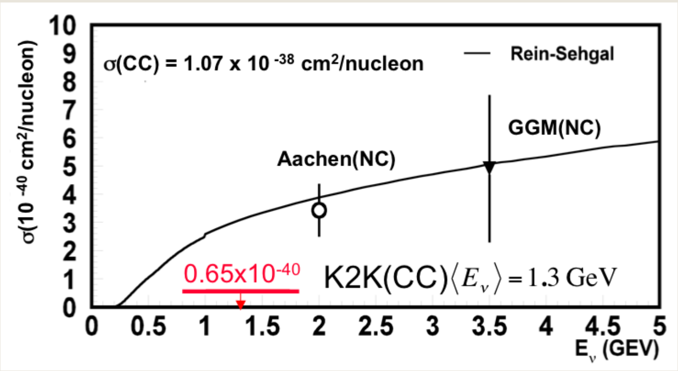
- SciFi → Water target→The first measurement of axial mass M_A
- in QE interactions in water.
- 8814 events from the K2K-I run and 5967 events from the K2k-IIa run.
- Data above $Q^2 > 0.2$ GeV^2 are fitted to obtain M_A as, $M_A = 1.18 \pm 0.03(stat) \pm 0.12(syst)$.
- 20% higher than previously measured.

Results:

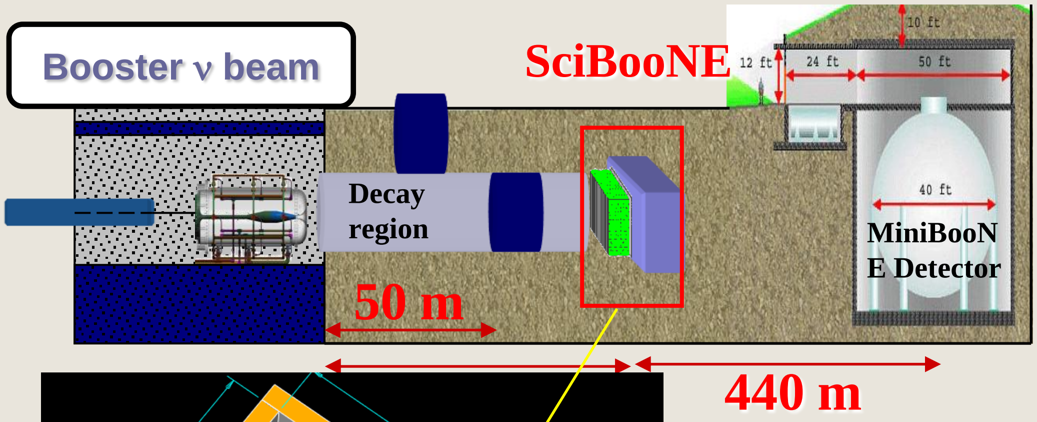
➢SciBar detector data→ Carbon target→ First search for CC coherent π^+ production at low energy.

➢Events with two reconstructed tracks are selected.
➢MC predicts excess events at low Q^2.
➢But fitting Q^2 distribution yields 7.6±50.4 events Expected 470 events.
➢No evidence for coherent production.

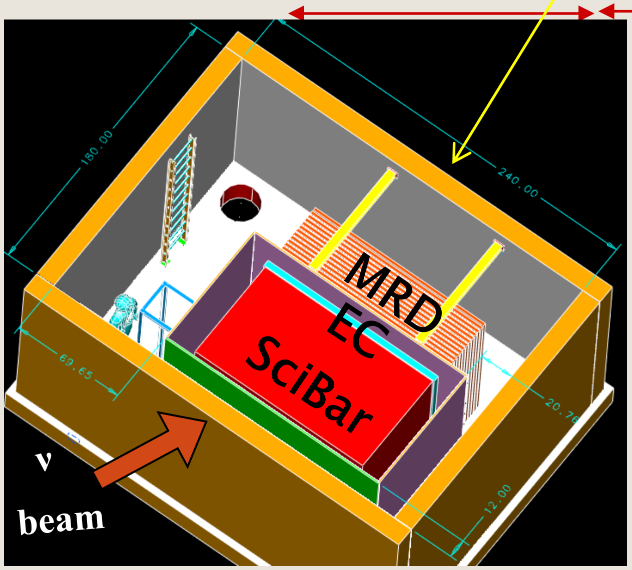




SciBooNE (SciBar+Booster Neutrino Detector):



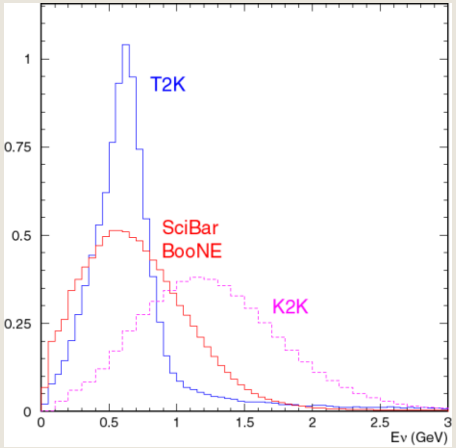
- Uses Booster Neutrino Beam (BNB) at FNAL (on axis-100 m from Be target).
- The energy peak of the ν beam is 0.7 GeV.
- The detectors:
SciBar , Electromagnetic calorimeter , Muon range detector.

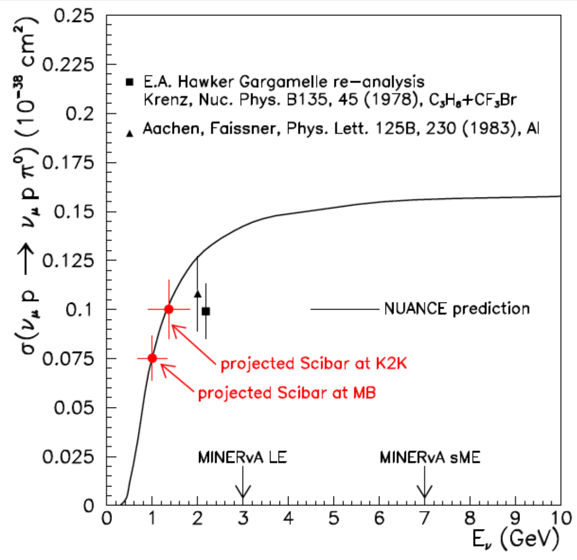


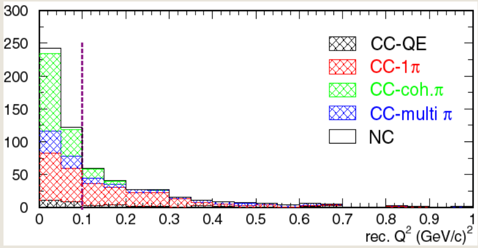
- 8 GeV protons from Booster with the rate being 4 X 10^{12} protons/1.6μs hit Be target (length 71 cm , diameter 1cm).
- and produces mesons,i.e, pions and kaons.
- The target is surrounded by magnetic focusing horn such that the polarity can be changed to get ν and anti-ν.
- This experiment collected both neutrino and antineutrino data in a period from June 2007 to August 2008.

Result:

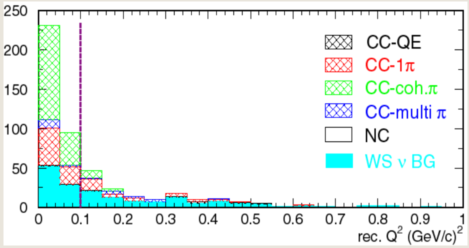
- 32000 ν_μ CCQE events .
- Lower statistics than MiniBooNE, but better Q^2 resolution
- Higher statistics than K2K SciBar, and lower **E_ν** .
- Higher event purity - less resonant contamination
- Confirm M_A measurement with low energy neutrinos and low-A target.
- NC1π^0 detection.
- Same detector used to measure NC1π^0 in two beams.
- ν_μ bar CC1π Coherent process





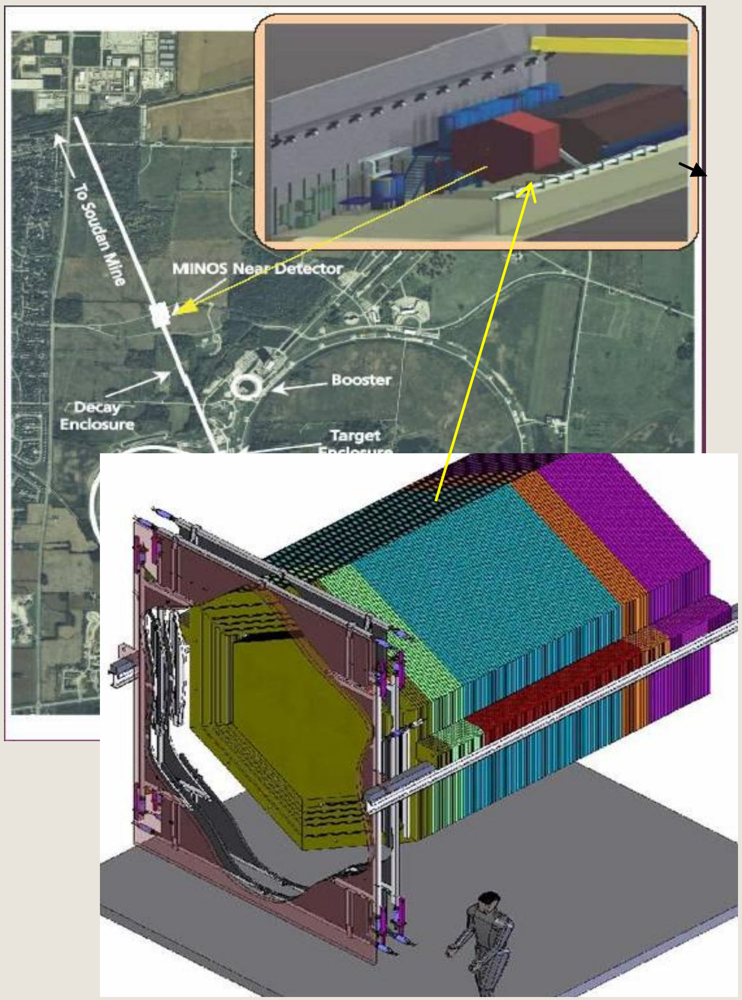


Neutrino event



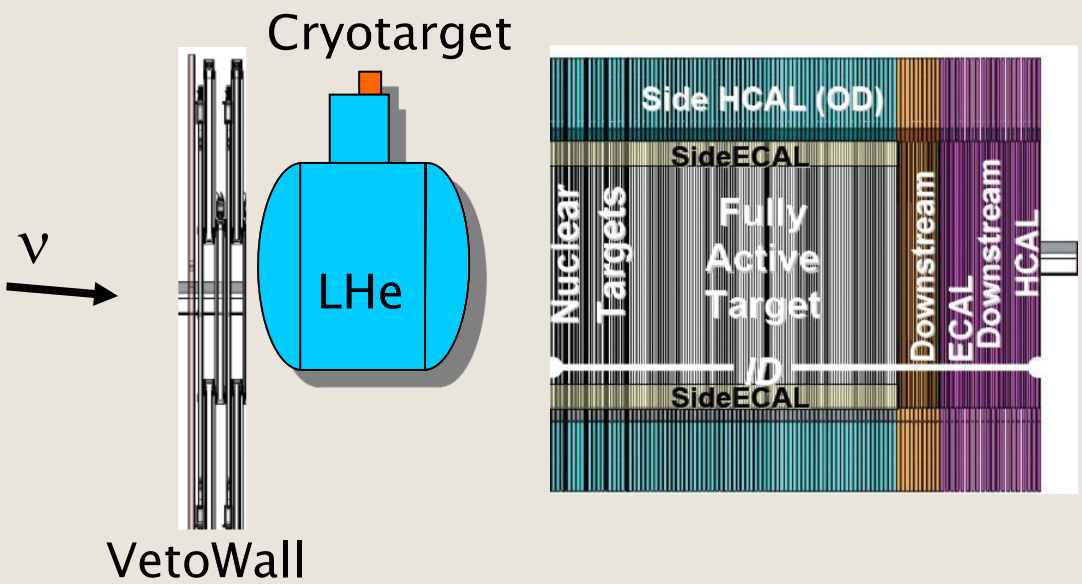
Anti neutrino event

MINERνA-Main Injector Neutrino Experiment ν-A:



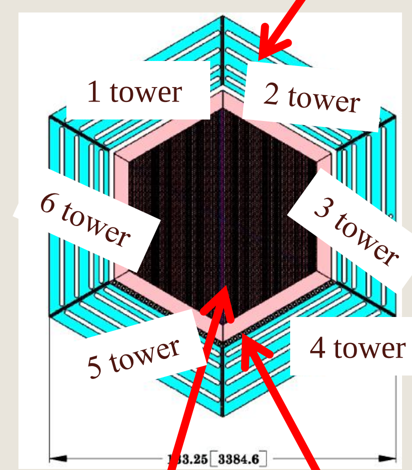
- It is a dedicated neutrino cross section experiment planned to run in the NUMI (Neutrinos at the Main Injector) beamline at Fermilab.
- The detector will be placed upstream of the MINOS Near Detector in the NuMI beam line.
- It will measure neutrino interactions across a wide range of neutrino energies (1-20GeV) as provided by the NuMI beam.
- The detector is being placed upstream of the MINOS Near Detector in the NuMI beam line.
- It will be the first detector to house a wide spectrum of nuclear targets (C to Pb) starting with three target materials C, Fe and Pb.
- Seeks to measure low energy neutrino interactions.

MINERνA Detector details:



- Downstream Calorimeters:
  20 modules, 2% active, sheets of lead (Electromagnetic Calorimetry) or steel (Hadronic calorimetry) between scintillator planes.
- Side Calorimeters:
  2 thin lead "rings" for side Electromagnetic Calorimetry, 4 layers of instrumented steel

Outer Detector (OD) Layers of iron/scintillator for hadron calorimetry: 6 Towers



Lead Sheets for EM calorimetry

Inner Detector Hexagon – X, U, V planes for stereo view

MINERνA Expects:

CCQE :

- Expect ~800,000 events
- Precision measurement of σ(Eν) and dσ/dQ over a wide dynamic range
- Precision determination of axial vector form factor (F_A), particularly at high Q^2
- Study of A-dependence (C, Fe and Pb targets)

Coherent π :

- Different nuclear targets will allow the first measurement of the A-dependence of σ_{coh} across a wide A range.

NC1p⁰ :

- Clean identification of π^0's.
- Extremely good π momentum reconstruction.
- Running in >1 GeV energy mode would allow understanding of $NC1\pi^0$ background.

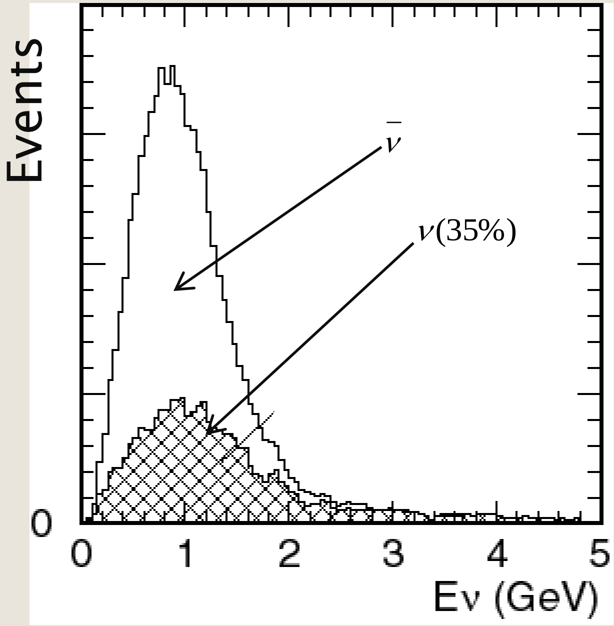
CC1π:

Expect ~ 1.6M total resonant, 1.2M 1π.

- Precision measurement of σ and dσ/dQ for individual channels.
- Detailed comparison with dynamic models, comparison of electro- & photo production.
- Study of the resonance-DIS transition region.
- Study of nuclear effects and A-dependence.

MINERνA Challenges:

- Experiments using magnetic horns suffer from *wrong sign* (WS) backgrounds ν_μ in $\overline{\nu_\mu}$ mode.
- For the Booster Neutrino Beam, WS backgrounds comprise ~35% of the total event rate.
- These must be removed from event samples for accurate antineutrino cross section measurements.
- Difficult for detectors without magnetic fields.

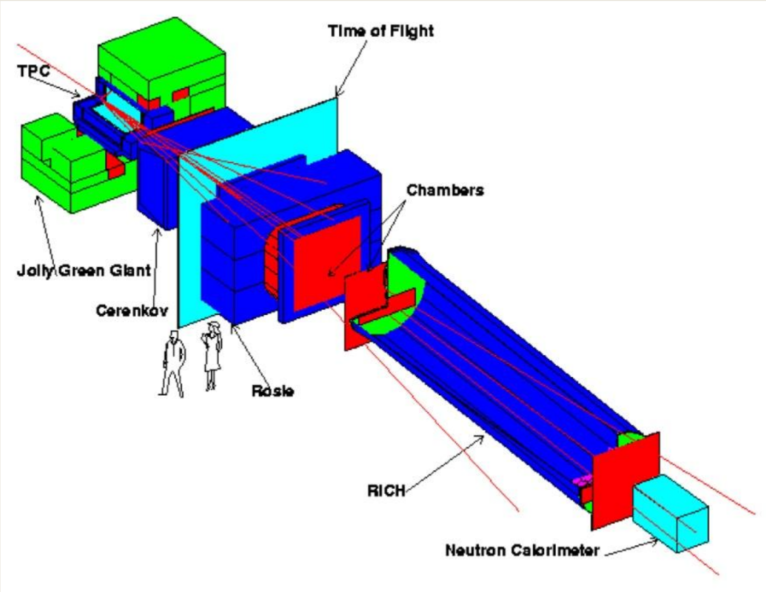


MIPP: Main Injector Particle Production Experiment:

- A fixed-target particle production experiment.

- TPC,
- Beam Chamber,
- RICh (Ring Imaging Cerenkov Counter).
- Caloriemeter.

- Primary proton beam of momentum120 GeV/c, secondary p,k and π beams of momentum 5-80 GeV/c from NUMI.
- Multiple targets – including liquid Hydrogen,and Uranium etc.)
- It permits detailed cross section measurements.



Conclusion :

- *We had a overview of different neutrino interactions and cross sections.*
- *We went through the details of different experiments like NuTeV,K2k,SciBooNE,MINERvA,MIPP.*
- *We had a view of the results both obtained and expected from the experiments.*

References:

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Thank you