Answering CCQE cross-section discrepancy at low energies

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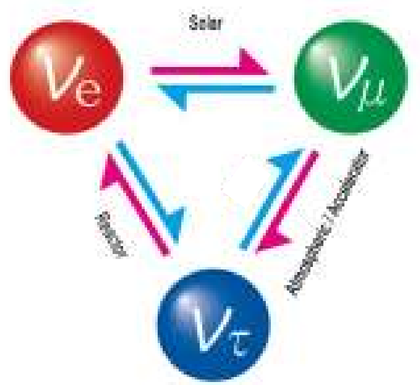
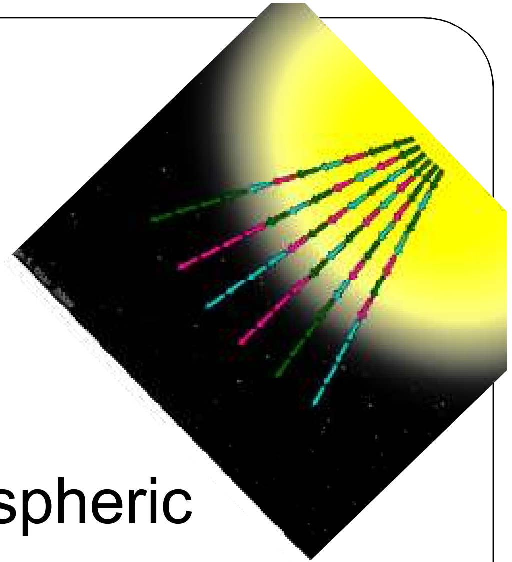
Neutrino

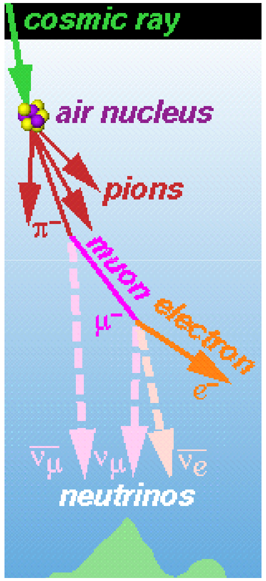
The *weakly* interacting neutral elementary particle



Come in 3 flavor

Neutrino puzzle

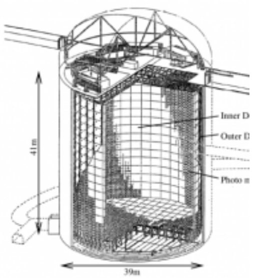




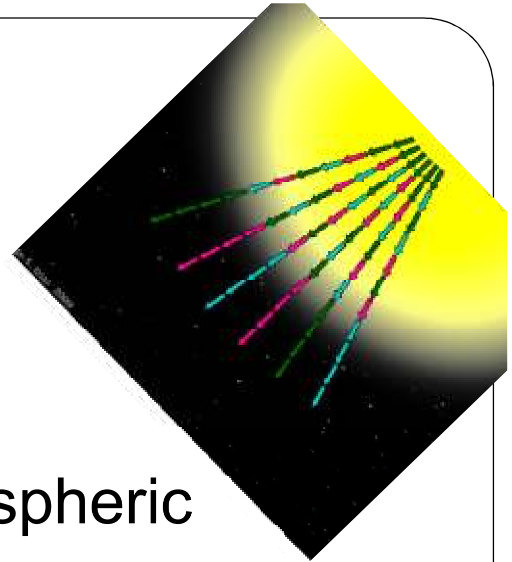
Long standing solar and atmospheric neutrino puzzle

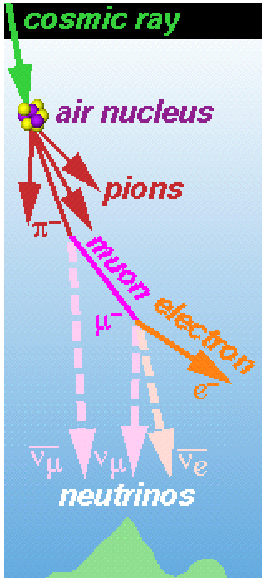
Measured number of neutrinos, less than the predicted number!!

Super-Kamiokande



PMNS' matrix





Long standing solar and atmospheric neutrino puzzle, solved

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

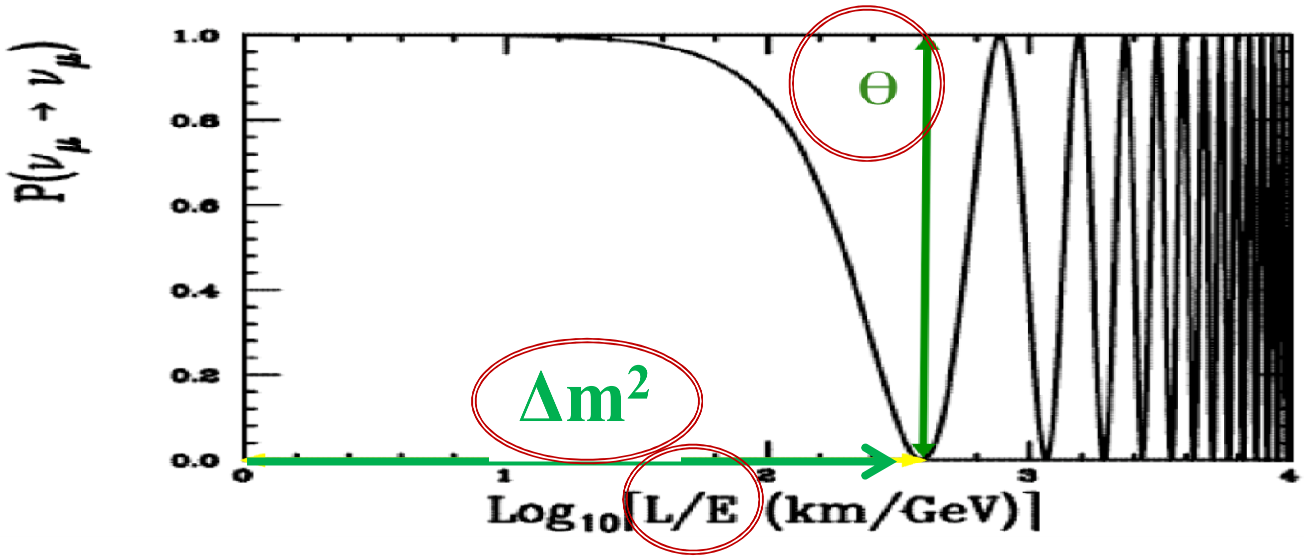
Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

T2K T2K

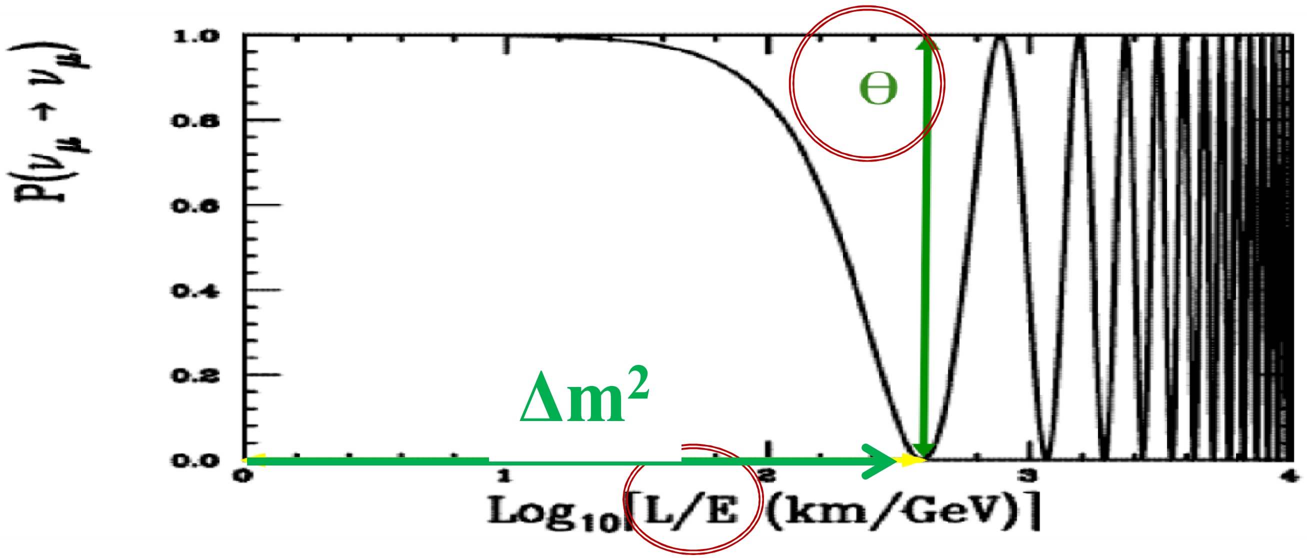
"Atmospheric ν"	"Reactor/Acc. ν"	"Solar ν"	Majorana phases;
$\sin^2 2\theta_{23} > 0.95$ (90% C.L.)	$\sin^2 2\theta_{13} = 0.098 \pm 0.013$	$\sin^2 2\theta_{12} = 0.857 \pm 0.024$	Not yet observed

Survival probability

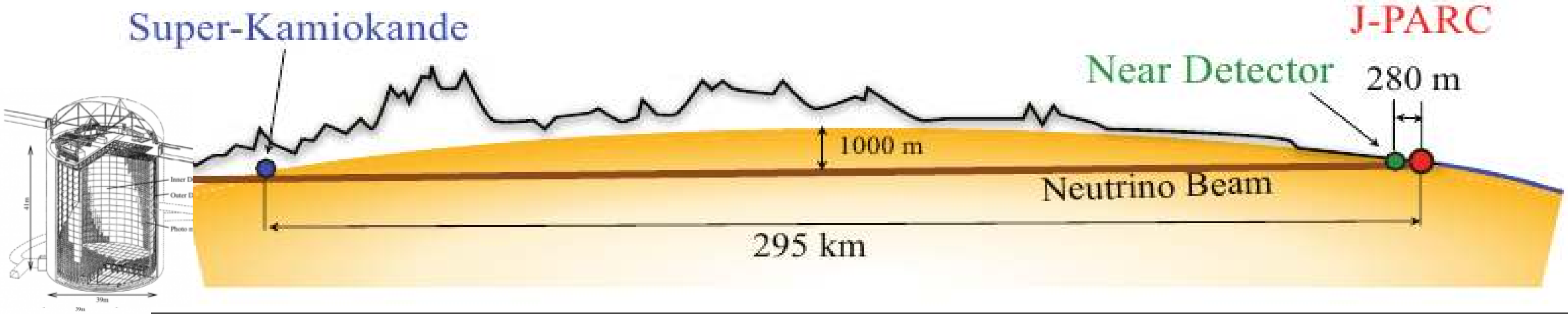


Massive neutrino oscillate from one flavor to another.

Survival probability

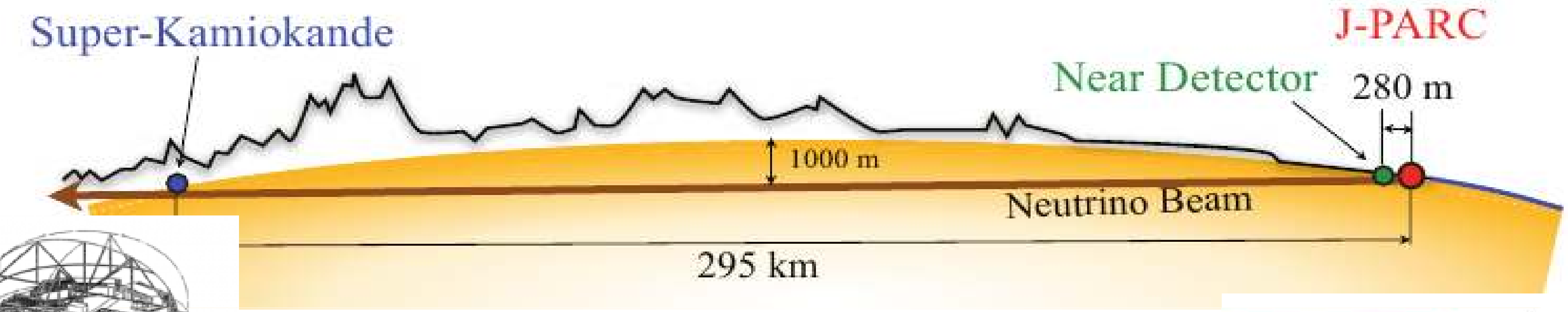


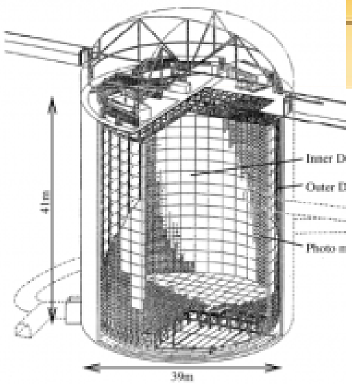
Massive neutrino oscillate from one flavor to another.



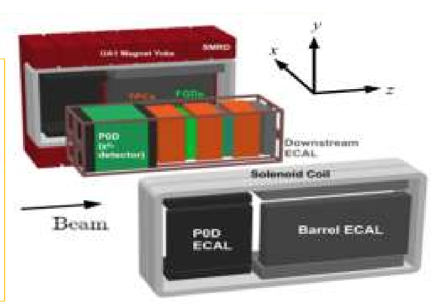
T2K

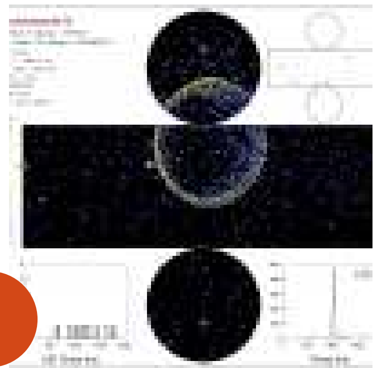
Long baseline accelerator experiment

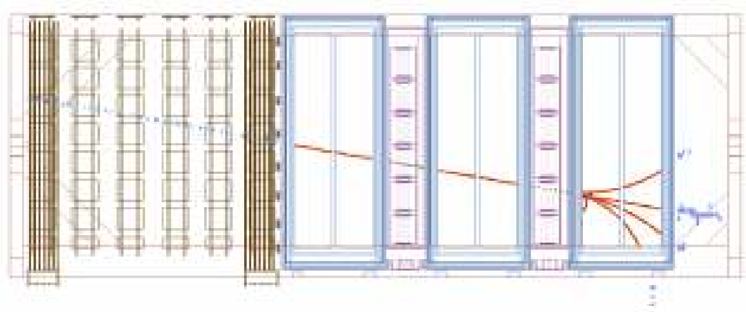




For precision measurement atmospheric parameters.

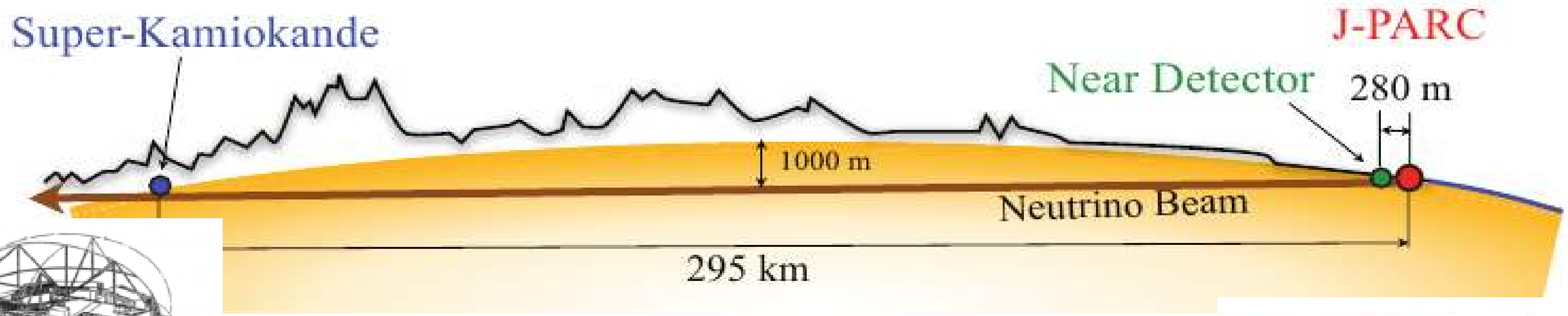


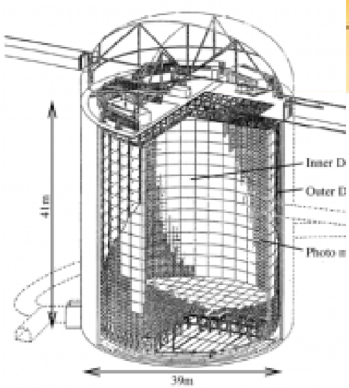




T2K

Long baseline accelerator experiment





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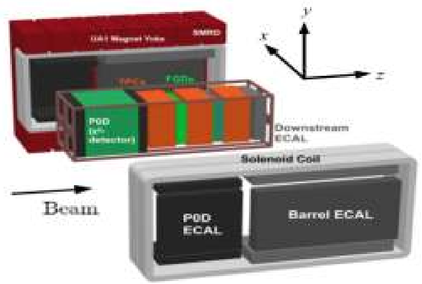

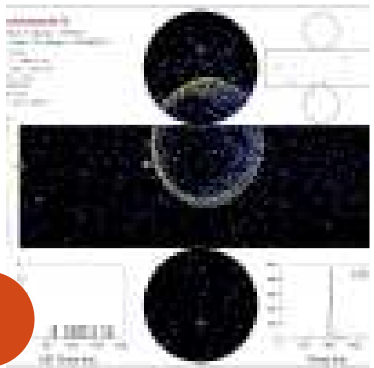

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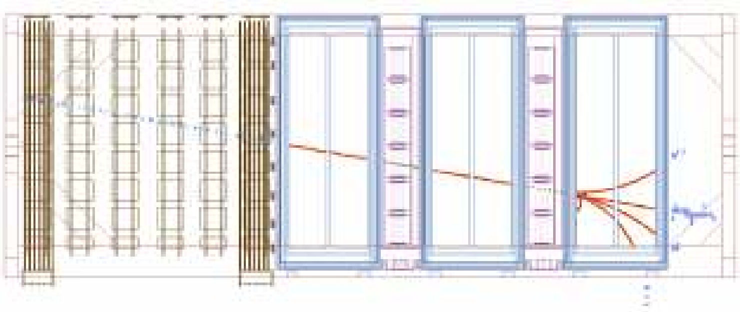
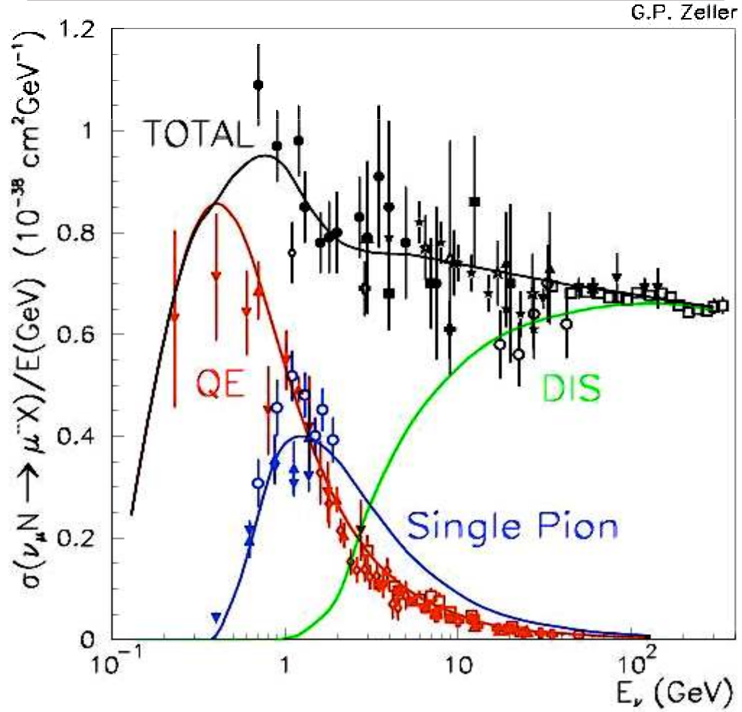
Neutrino Interaction



Neutrino Interaction

Charged Current:
Exchange of $W^{\pm}$ boson
Neutral Current:
Exchange of Z boson.



- **quasi-elastic scattering (QE)**
  (nucleon)

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

- **single π production** **(excitation of nucleus)**

$$\nu_\mu + N \to \mu^- + N' + \pi$$

- **deep inelastic scattering (DIS)**
  (quark)

$$\nu_\mu + N \to \mu^- + X$$

- **elastic ν-electron scattering**

$$\nu_\mu\, e^- \to \nu_\mu\, e^-$$

(μ could be any lepton)

CCQE model

- Scattering cross-section of neutrinos off the nucleon is given by the Llewellyn-Smith formula / Smith-Moniz

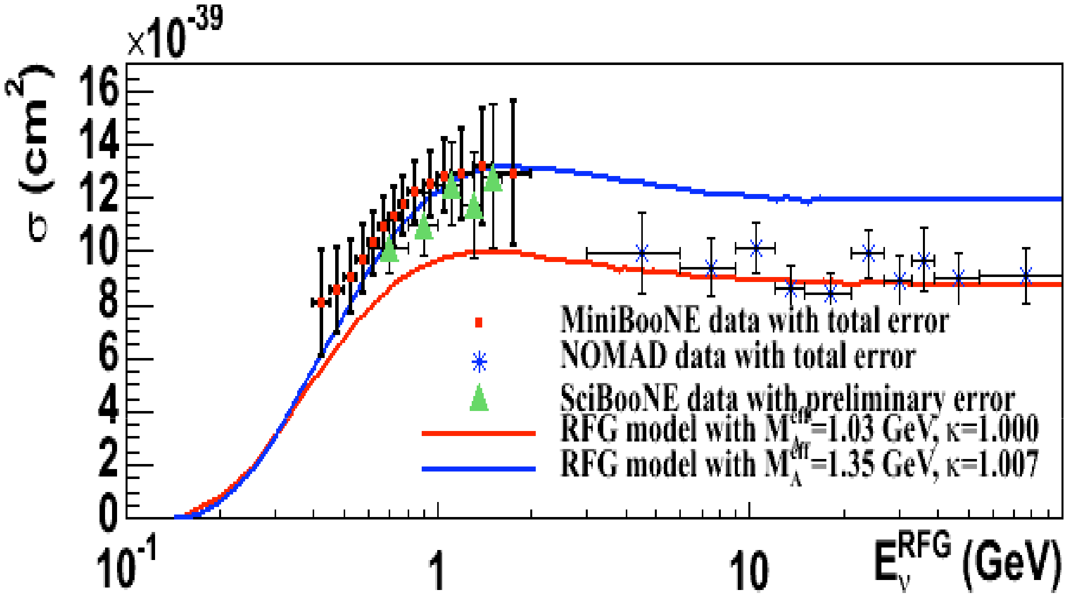
$$\frac{\partial\sigma}{\partial Q^2} = \frac{M^2 G_F^2 \cos\Theta}{8E_v^2}\left(A(Q^2) \pm \frac{B(Q^2)(s-u)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^4}\right)$$

- A, B, C are function of Q^2 , with coefficients called form-factor.
- Form factor parameterize hadronic information and are measured experimentally.

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

World average value of M_A=1.01

Cross-section discrepancy



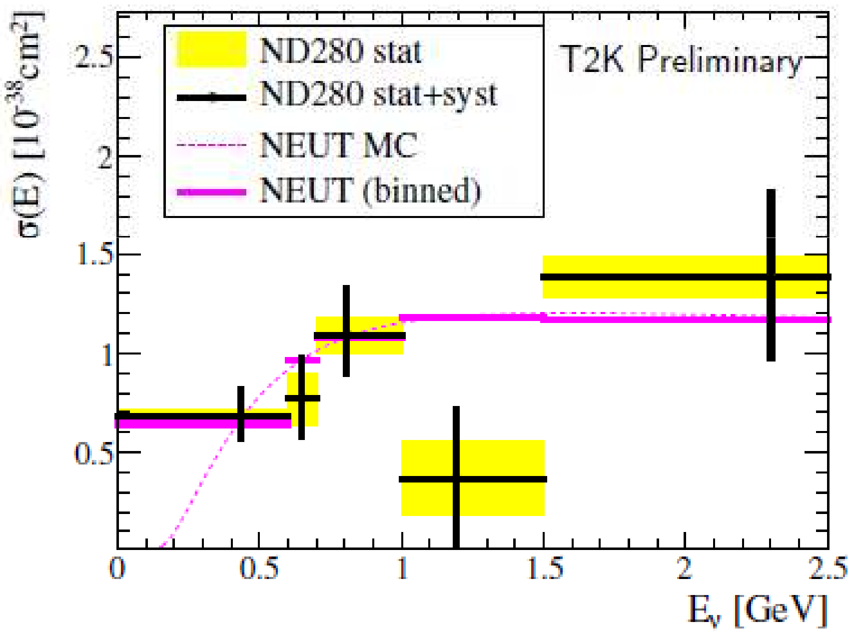
World average (D2)	1.020±0.03
K2K SciFi (O)	1.200±0.12
K2K SciBar (C)	1.140±0.10
MiniBooNE (C)	1.350±0.17
MINOS (Fe)	1.190±0.17
NOMAD (C)	1.050±0.06

MiniBooNE QE data was fitted with higher M_A value 1.35

Also its QE sample has different muon kinematics.

Difference in cross-section along Q^2 reflects incompleteness of cross-section model.

T2K cross-section measurement



Fit to T2K data also agrees on higher value of Ma =1.21

QE signal

MiniBooNE : only muon (1track) no pion

- may include, multiple nucleon (not CCQE)

NOMAD: only muon (1track) or muon+proton (2 track)

- Pure-QE Sample

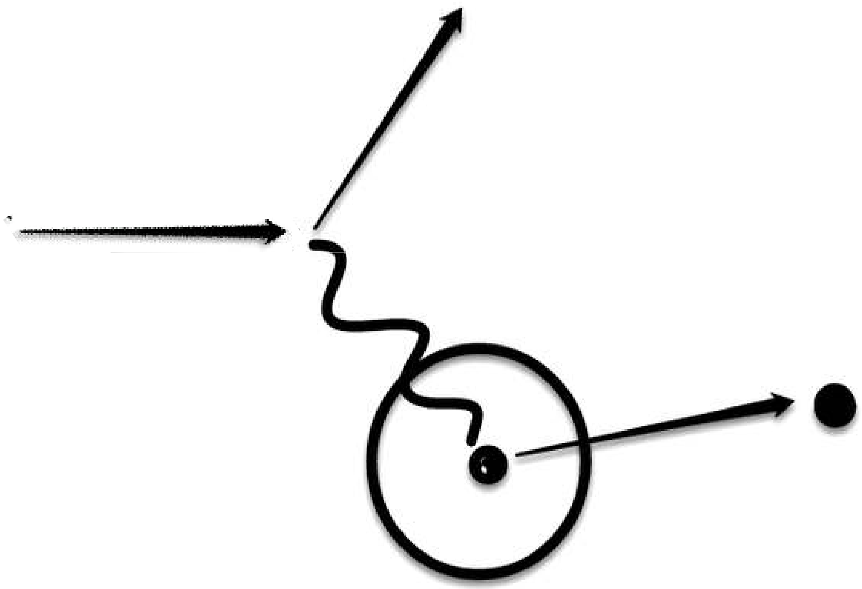
MinibooNE selected QE-like events which may includes additional interaction not foreseen before.

Possible reasons for the excess

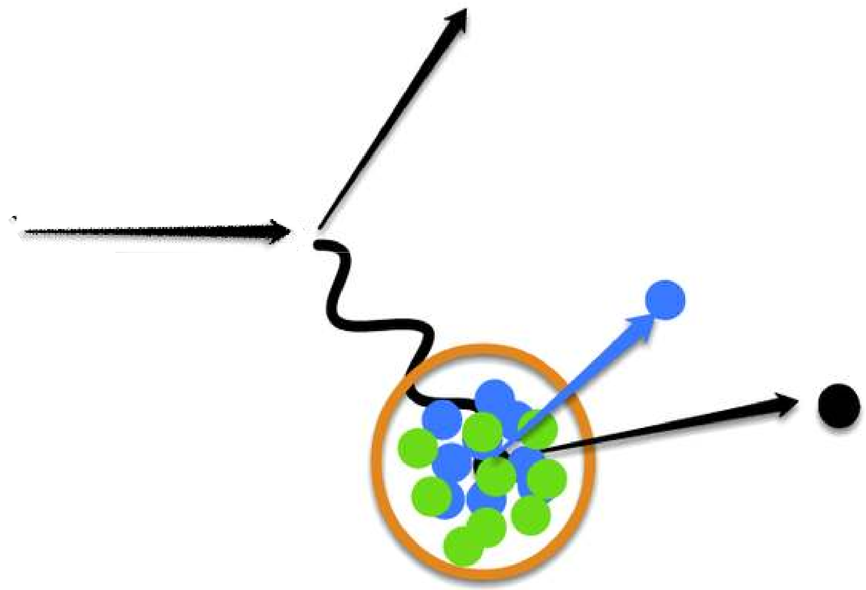
- Could there be some mode of interaction we failed to observe before?
  - Nuclear medium can alter QE free nucleon scattering prediction .
- Why didn't we see it before?
  - Bubble chamber experiments typically employed light targets (H2 or D2)
  - Required the detection of both ,the final state muon and single nucleon.
- If the data fits with Ma=1.35, good enough. Why not use that?
  - Muon kinematics altered => mis-reconstruction of the neutrino energy.

Need a model to explain this effect.

QE with Impulse Approximation



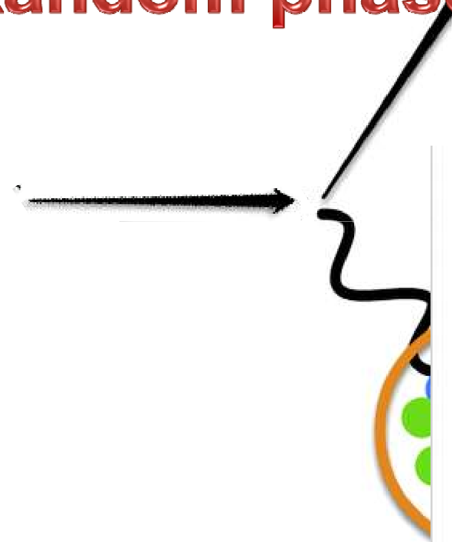
Nuclear correlation



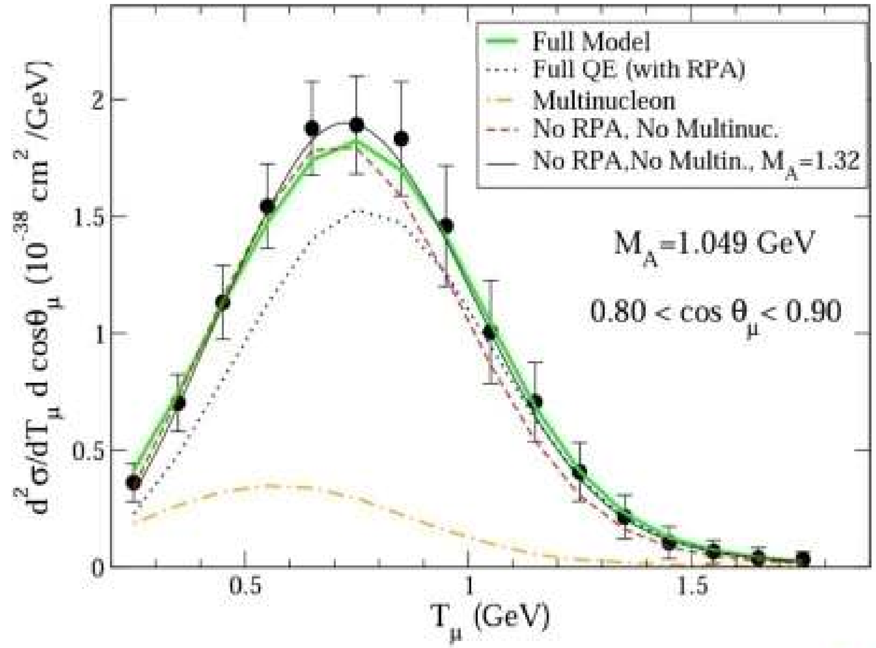
Nuclear correlation

Multinucleon ejection model +

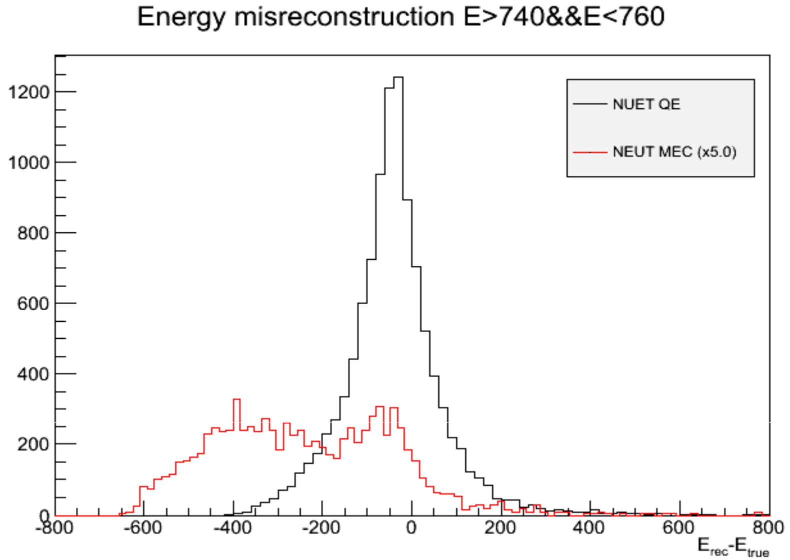
Random phase approximation



Nieves multinucleon + QE with RPA fits MiniBooNE data.



Concern for Oscillation Analysis



Black: only QE sample. Red : npnh events reconstructed as QE using formula given below

$$E_{\nu}^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

- Multi-nucleons interaction (npnh) have different lepton kinematics than CCQE.
- If tagged as CCQE leads to **mis-reconstruction of neutrino energy.**
- Consequently affects oscillation analysis
- Of concern at higher statistics as the statistical errors are reduced.

Emphasizing the need to have the models in the neutrino generators .

Updating Monte Carlo neutrino generator, NEUT

(official generator of T2K)

<u>Multinucleon ejection:</u>

- Nieves based on many body formalism, for the energy regions of QE and Δ excitation and the dip between the two.
- Additional correlated pair of nucleons

<u>Random Phase Approximation:</u>

- Effect of change in strength of electroweak coupling of nucleon in a nucleus due to presence of strongly interacting nucleons.
- Accounts for medium polarization effect in 1p1h.
- Improves prediction at low Q2

Outlook

Next, I will test these models against T2K data.

A model dependent cross-section fit with new models in generator and more statistics.

Thank you.

Cross-section measurement

$$N_\nu = \Phi(E) \times \sigma(E) \times T$$

$\Phi(E) =$ Neutrinos Flux
$\sigma(E)$ = interaction Cross-section
T = number of nucleons. (Target, Size of the detector)
$N_\nu =$ *Observed neutrino event*

<u>To increase the number of observed events</u>

- **Increase the flux**
- Increase the energy ($\sigma_\nu \propto E$). But fixed by oscillation parameter.
- **Increase the density of nucleon by changing the target to heavy element**.

Higher statistics is achieved by increasing flux and changing over to heavy nucleus target.

Understanding the difference

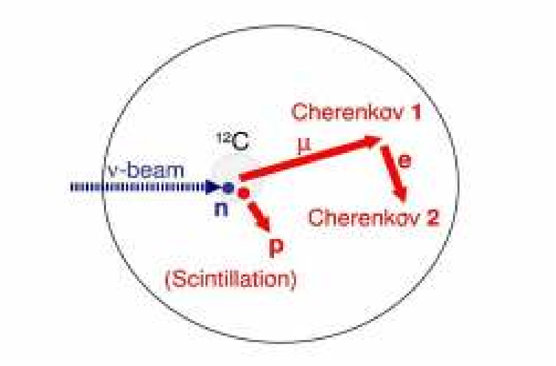
MiniBoone

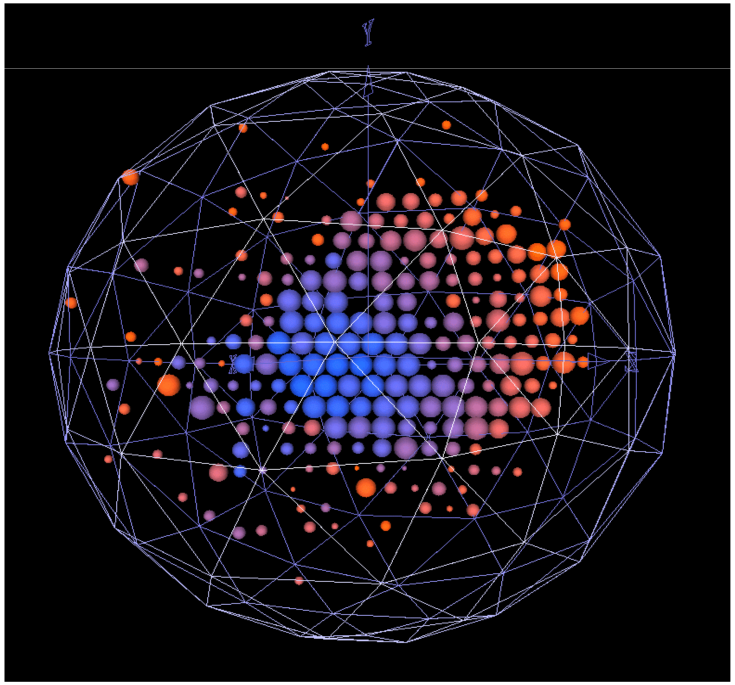
- 800t Cherenkov detector, filed with mineral oil (C) Energy ~ 700 MeV

First experiment to make double differential cross-section plots possible because of high statistics it had. (model independent.)

<u>QE Selection:</u>

- muon identified with decay electron, no direct selection on proton
- CC1π background are constrained based on CC1π selected event

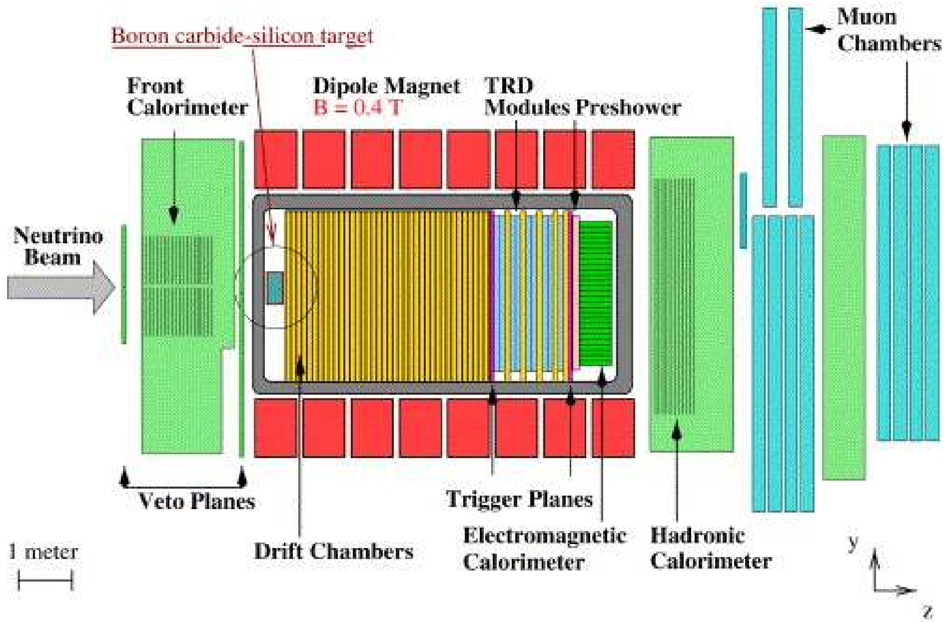




Understanding the difference

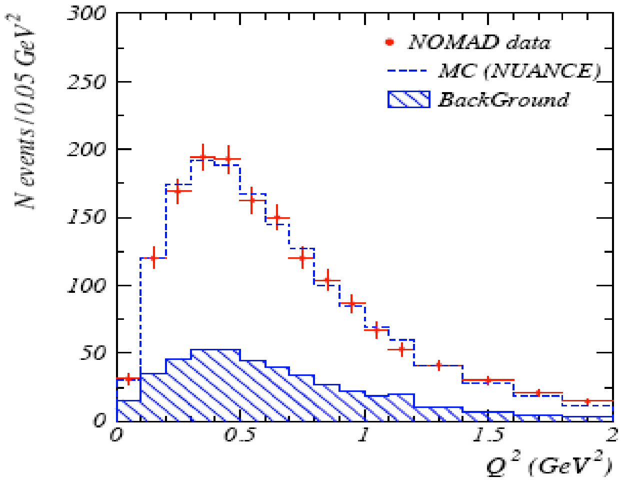
NOMAD

- Drift chambers with hadronic calorimeters and muon detectors situated in magnetic field (Eν ~24 GeV, carbon target)

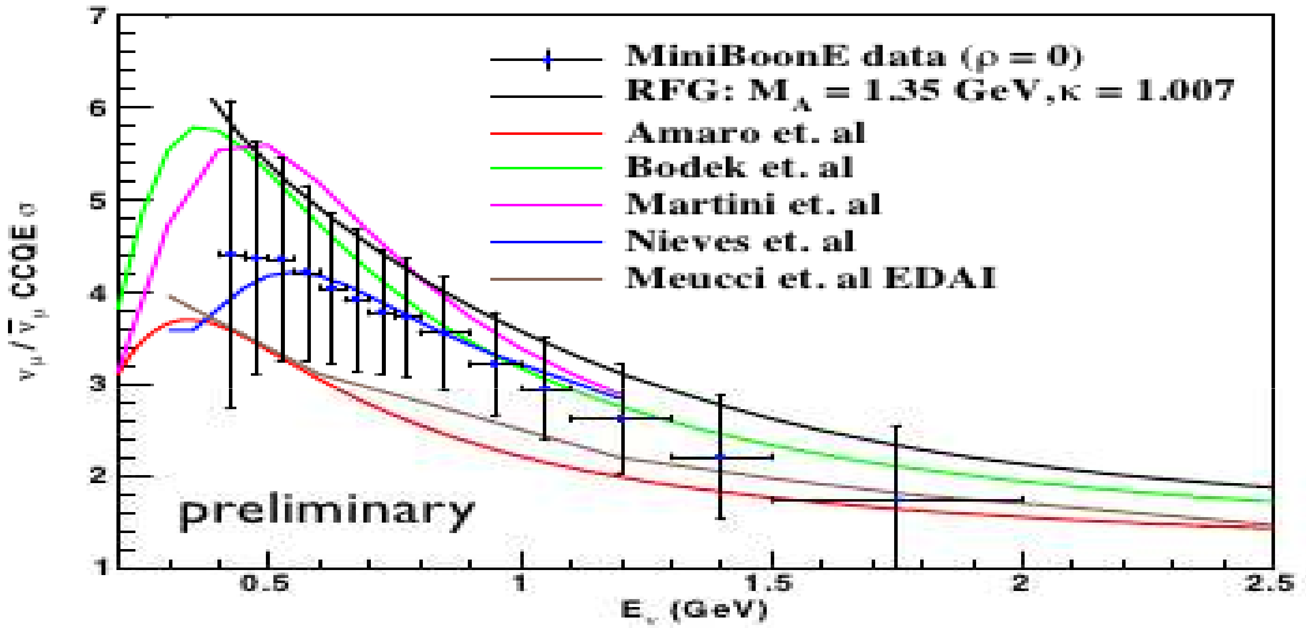


<u>QE Selecction</u>:

- "1 track" + "2 track" (muon, proton,~3.5k) samples



Theory rescue, Multi-nucleon ejection models



- Multi-nucleon ejection model (Nieves' et al) which best fit the data below 1.5 GeV. (now extended to higher energies within limit q3<1.2)
- Transverse enhancement model (TEM, Bodek et. al.), in the region where Nieves' model fails.

Nieves multi-nucleon ejection model.

- Successfully tested electron-nucleus measurements.
- Extended many body formalism developed for computation of inclusive electron-nucleus cross section in the energy regions of QE and Δ excitation and the dip between the two.
- This formalism systematically incorporates different gauge boson absorption terms which will contribute to multi-nucleon ejection.
- Nuclear effects like Random Phase approximation (phase polarization) are taken into account.

Recipes for W-boson absorption.

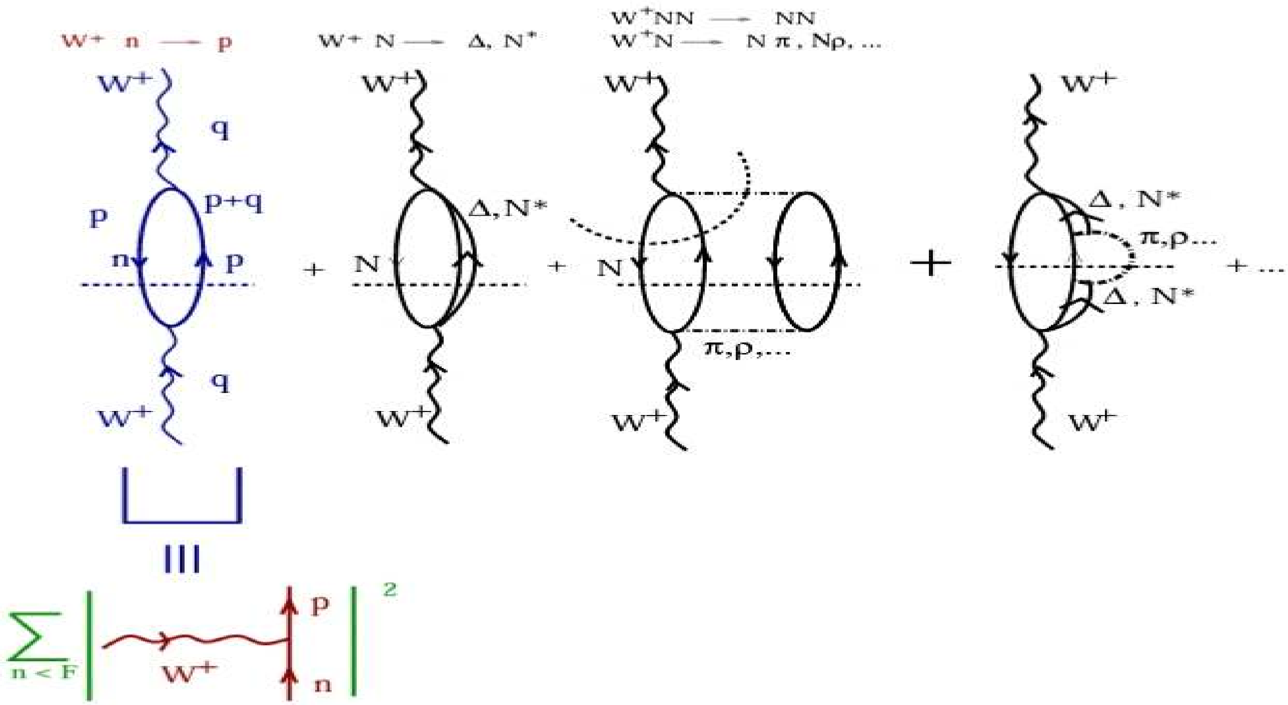


Figure 2.3: Diagrammatic representation of some mechanisms contributing to the W^+-selfenergy

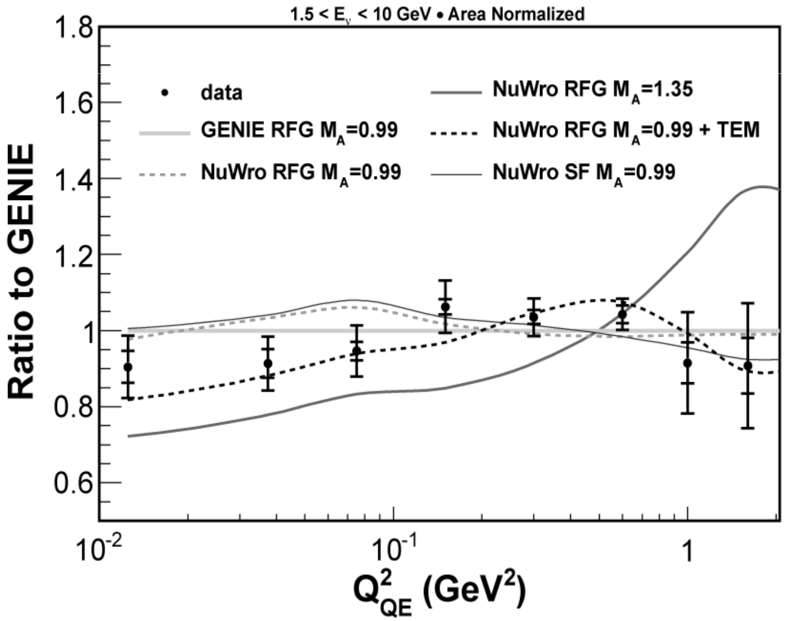
- absorption by one nucleon.
- absorption by pair of nucleon or more.
- Real or virtual meson production
- Excitation of Δ isobars and higher resonances dof

.

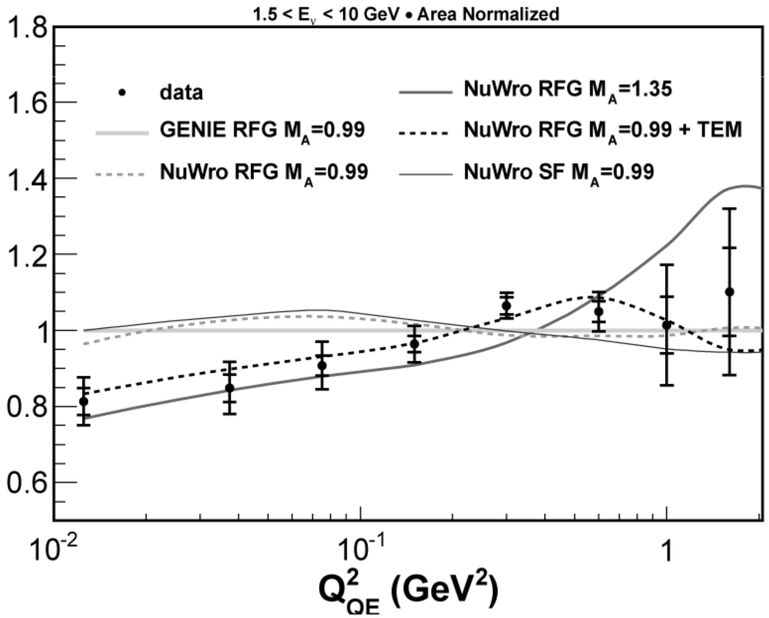
Validation by Minerva

- Uses finely segmented scintillator detector at Fermilab to measure ν_μ & $\overline{\nu_\mu}$ QE interactions on nuclear targets.
- At energies between 1.5 and 10 GeV .

Neutrino



Antineutrinos



Minerva cross-section results best agreement with a TEM with MA = 0.99 GeV/c2

Llewellyn-Smith formula for QE scattering

- Scattering cross-section of neutrinos off the nucleon is given by the Llewellyn-Smith formula / Smith-Moniz (RFG)
  - Impulse Approximation : gauge boson is absorbed by just one nucleon .
  - Use Fermi Gas model , i.e. P (nucleon) < P_f max
    ($P_f$max is function of #nucleons.)

$$\frac{\partial\sigma}{\partial Q^2} = \frac{M^2 G_F^2 \cos\Theta}{8E_v^2}\left(A(Q^2) \pm \frac{B(Q^2)(s-u)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^4}\right)$$

G_F is the Fermi constant, | M is the average nucleon mass,| θ_C is the Cabbibo angle; | E is the neutrino energy | s and u are Mandelstam variables

Form Factor

- A, B, C are function of Q^2 , with coefficients called form-factor.
- Form factor parameterize hadronic information and are measured experimentally.
  - Two vector form factor are know from electron scattering experiments.
  - Pseudo-scalar form factor contribution is negligible.
  - Only unknown Axial mass form factor, is measured using neutrino scattering.
  - Axial form factor in the dipole form is dependent on two parameters.
    - F_A is precisely known from beta decay experiment.
    - **So the only parameter left was M_A**

$$F_A^{dipole} = \frac{F_A(0)}{(1-\frac{q^2}{M_A^2})^2}$$

World average value of M_A 1.01

Sterile neutrino global Fit results

arXiv:1311.1335v1

	3+1 LOW	3+1 HIG	3+1 noMB	3+1 noLSND	3+2 LOW	3+2 HIG	3+1+1 LOW	3+1+1 HIG
$\chi^2_{\rm min}$	291.7	261.8	236.1	278.4	284.4	256.4	289.8	259.0
NDF	256	250	218	252	252	246	253	247
GoF	6%	29%	19%	12%	8%	31%	6%	29%
$(\chi^2_{\rm min})_{\rm APP}$	99.3	77.0	50.9	91.8	87.7	69.8	94.8	75.5
$(\chi^2_{\rm min})_{\rm DIS}$	180.1	180.1	180.1	180.1	179.1	179.1	180.1	180.1
$\Delta\chi^2_{\rm PG}$	12.7	4.8	5.1	6.4	17.7	7.5	14.9	3.4
$\rm NDF_{PG}$	2	2	2	2	4	4	3	3
$\rm GoF_{PG}$	0.2%	9%	8%	4%	0.1%	11%	0.2%	34%
$\Delta\chi^2_{\rm NO}$	47.5	46.2	47.1	8.3	54.8	51.6	49.4	49.1
$\rm NDF_{NO}$	3	3	3	3	7	7	6	6
$n\sigma_{\rm NO}$	6.3σ	6.2σ	6.3σ	2.1σ	6.0σ	5.8σ	5.8σ	5.8σ