Multi-nucleon interaction to answer CCQE cross-section discrepancy

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INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

Neutrino Physics: Present and Future

Erice – Sicily

UNIVERSITÄT
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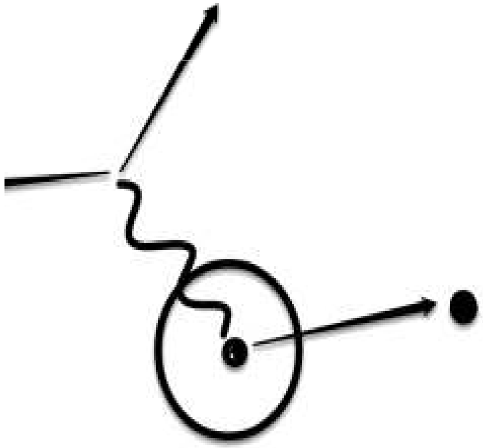
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

T2K

Outline



- Brief introduction to neutrino interactions
- QE cross-section discrepancy
- Probing the cause
- Possible solutions
- Concern for oscillation expt.
- Recent results
- Efforts at T2K

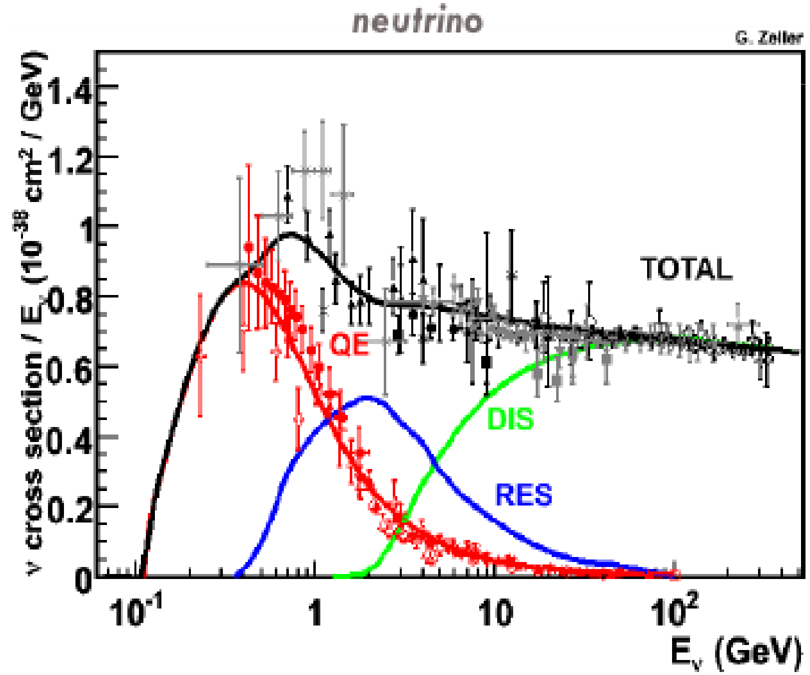
Brief introduction to ν interactions

Charged Current:

Exchange of $W^{\pm}$ boson

Neutral Current:

Exchange of Z boson.



http://rmp.aps.org/abstract/RMP/v84/i3/p1307_1

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

$$\nu_l + n \rightarrow l^- + p$$
$$\nu_l + n \rightarrow \nu_l + p$$

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

$$\nu_l + N \rightarrow l^- + N' + \pi$$
$$\nu_l + N \rightarrow \nu_l + N' + \pi$$

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

$$\nu_l + N \rightarrow l^- + X$$
$$\nu_l + N \rightarrow \nu_l + X$$

- **Elastic ν-electron scattering**

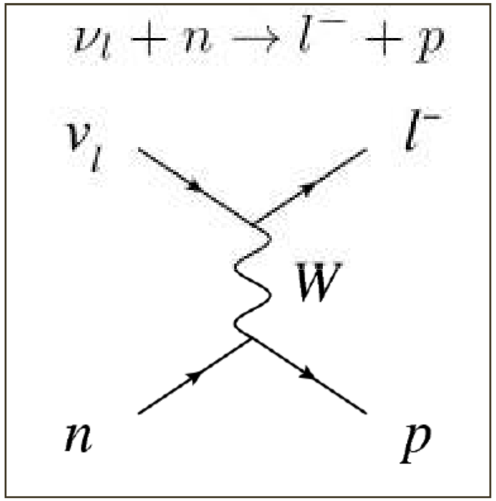
$$\nu_l\, e^- \rightarrow \nu_l\, e^-$$

History of neutrino QE scattering

- Extensively studied in 60-90s on light nuclei, focus then moved towards DIS for more statistics.
- After discovery of neutrino oscillations, accelerator experiments were built which operated in the low energy regime. And moved to heavy target detectors to increase statistics.
- Most of the neutrino energy is carried away by the lepton so easy to reconstruct.

CCQE

$$\nu_l + n \to l^- + p$$



QE channel was one of the best understood channel. *

(If impulse approximation holds good)*

Llewellyn Smith formula for QE scattering

- In present neutrino generators we use scattering cross-section of neutrinos off the nucleon, given by the Llewellyn Smith formula / Smith Moniz (RFG).
  - ➢ Impulse Approximation : gauge boson is absorbed by just one nucleon .
  - ➢ Use Fermi Gas model , free nucleon in mean field,
    with P (nucleon) < Fermi surface momentum

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

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,

A, B, C are functions of Q^2, with coefficients called form-factor.

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261

Form Factors

- Form factors parameterize hadronic information and are measured experimentally.
  - Two vector form factors are know from electron scattering experiments.
  - Pseudo-scalar form factors contribution is negligible.
  - Only unknown is axial form factor, and is measured using neutrino scattering.
- Axial form factor in the dipole form is dependent on two parameters.
  - F_A (0) is precisely known from beta decay experiment.
  - **So the only parameter left was axial mass form factor M_a**

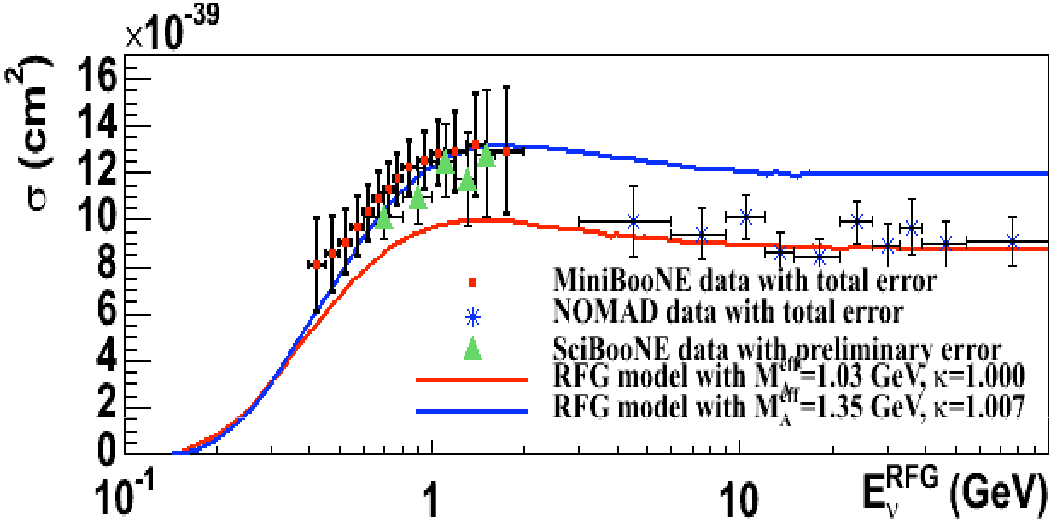
Nominal value of $M_a = 1.02$

(from pre-MiniBooNE era, from fit to BNL, ANL, FNAL data)

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

BNL: Baker, PRD **23**, 2499 (1981)
ANL: Miller, PRD **26**, 537 (1982)
FNAL: Kitagaki, PRD **28**, 436 (1983)

MiniBooNE cross-section discrepancy

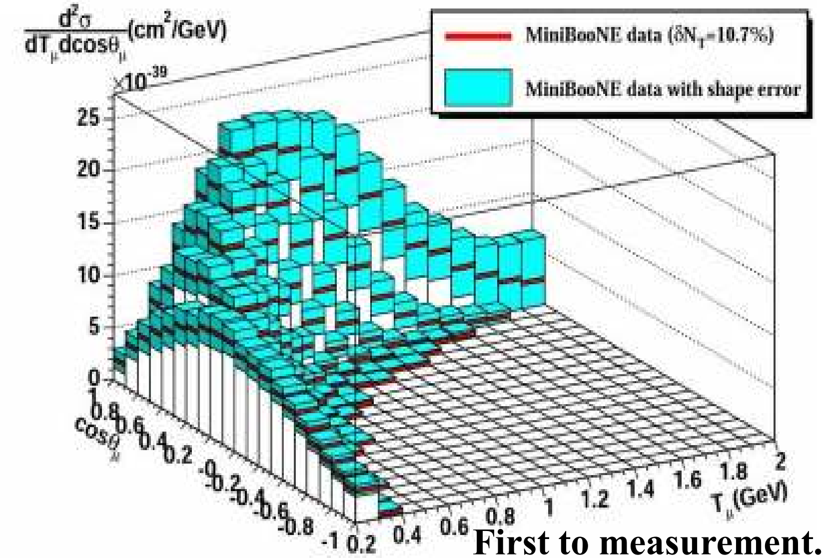


World average	1.020±0.03
K2K SciFi (O)	1.200±0.12
K2K SciBar (C)	1.140±0.10
MiniBooNE (C)	1.350±0.17
MINOS (Fe)	1.190±0.17
NOMAD (C)	1.050±0.06

MiniBooNE QE data,

- ➢ Fitted well with higher value of M_A 1.35GeV.
- ➢Different muon kinematics.

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



First to measurement.

T. Katori, IU, Ph.D. Thesis

arXiv:1107.3400v1 [hep-ex] 18 Jul 2011

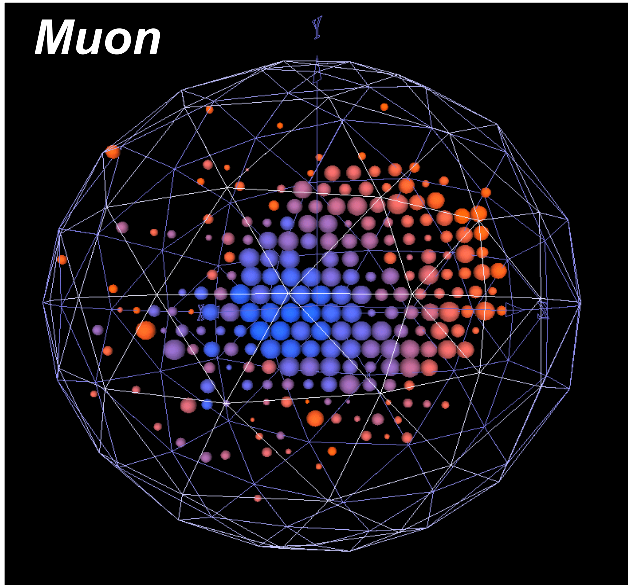
Understanding the differences

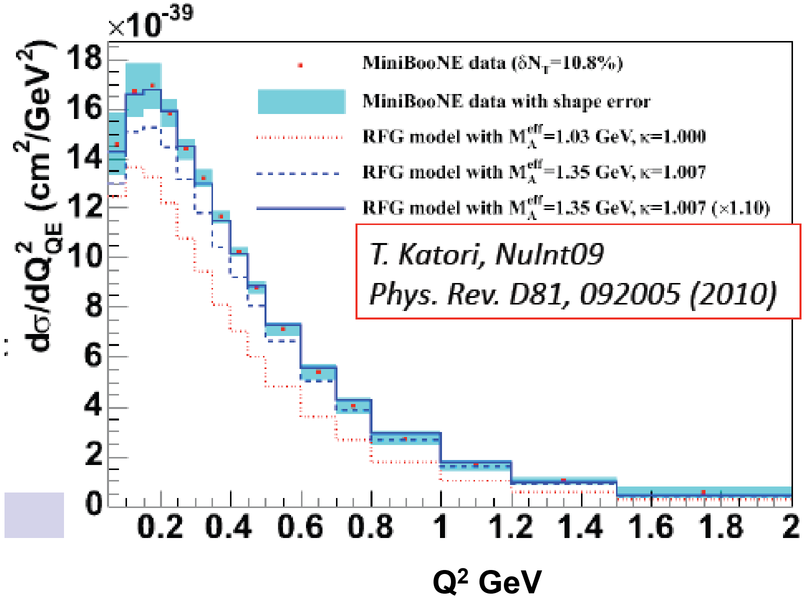
MiniBooNE

- 800t Cherenkov detector, filled with mineral oil (C)
- $< E_\nu > \sim$ 0.8 MeV
- 4π detector

<u>QE Selection:</u>

- Muon identified with its decay to electron,
- Protons are below Cherenkov threshold, so left undetected.
- CC0π background is constrained based on CC1π sample.
- Model dependent subtraction for other backgrounds.



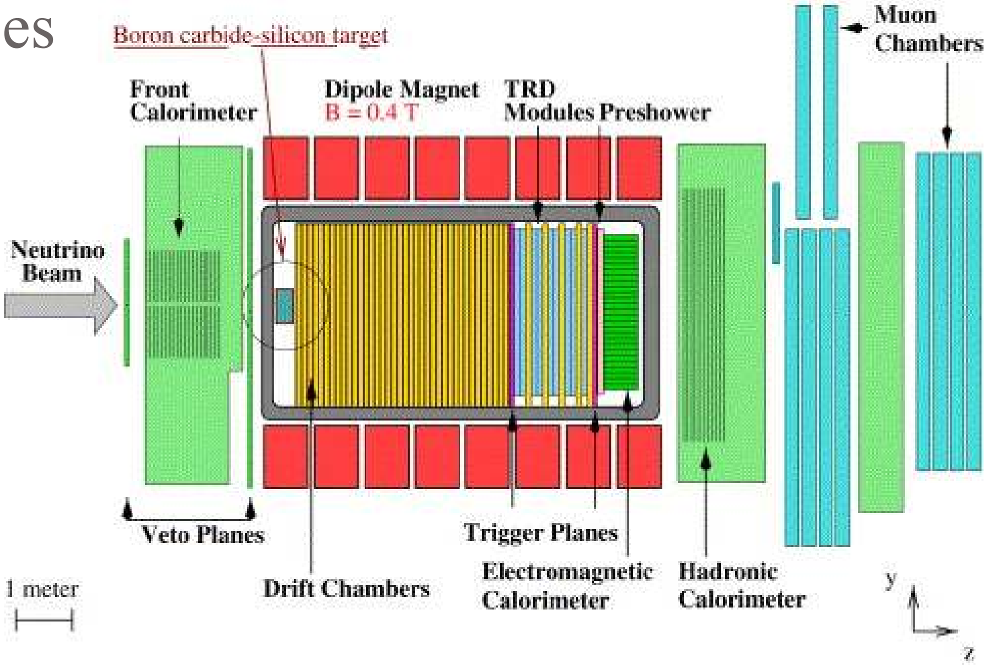


T. Katori, NuInt09
Phys. Rev. D81, 092005 (2010)

Understanding the differences

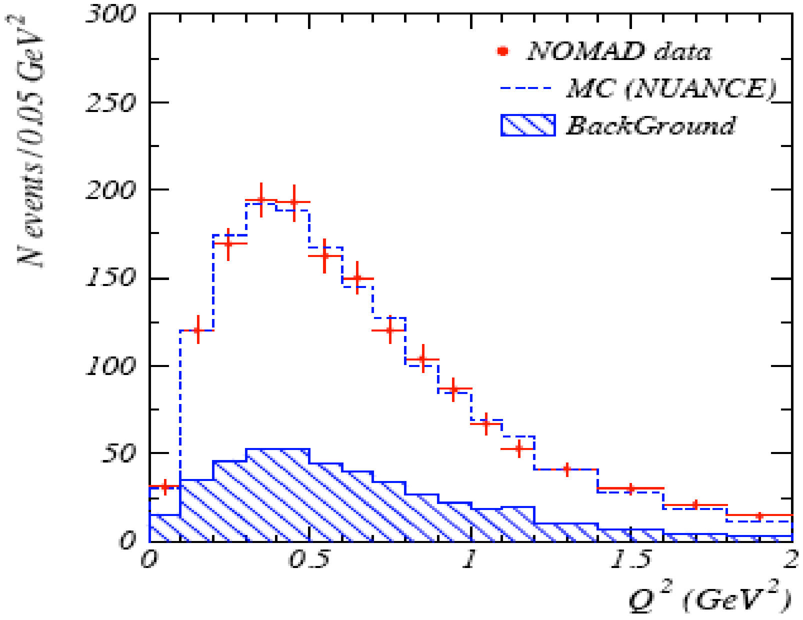
NOMAD

- Drift chambers with hadronic calorimeters and muon detectors placed in magnetic field
- <Eν> ~24 GeV,
- carbon target



<u>QE Selection</u>:

- “1 track” muon only &
- “2 track” muon + proton



V. Lyubushkin, NuInt09, Eur.Phys.J.C63:355-381,2009

Possible reasons for the excess

Could there be some mode of interaction we failed to observe before?

Nuclear correction in case of neutrino-nucleus scattering could alter QE free nucleon scattering prediction significantly.

MiniBooNE QE sample selection may include,

- Multinucleon interactions (2p2h known from electron scattering expt.)
- CC1Pi with topology altered by FSI (accounted for)

While NOMAD has,

- Strict cut on CCQE selection
- In addition, it sees lesser phase space than MiniBooNE.

***MiniBooNE selected QE-like events including unforeseen interactions*.**

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-nu-cross-sections.pdf

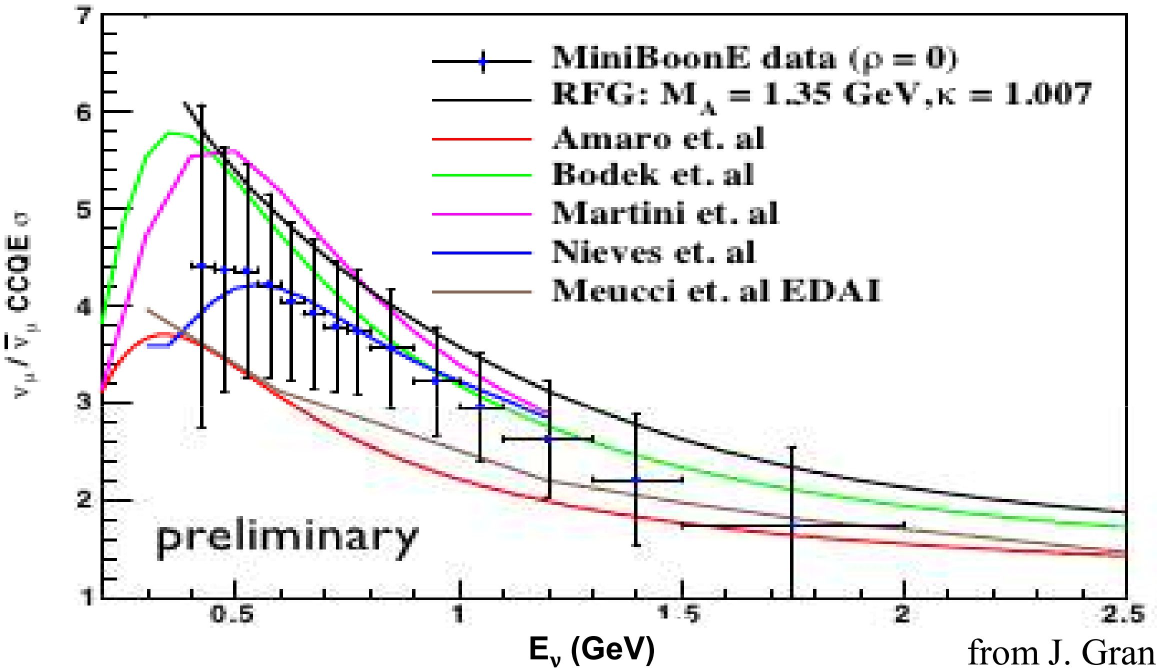
Possible reasons for the excess

- Why didn't we see it before?
  - Most of the bubble chamber experiments typically employed light targets (H2 or D2)
  - Required both the detection of the final state muon and single nucleon.

- If the data fits with Ma=1.35, good enough. Why not use that?
  - Ma form factor is an absolute constant by definition, not a parameter which could be target and energy dependent.
  - Muon kinematics are also altered, which will lead to misreconstruction of the neutrino energy.

Need a model which explains this effect.

Many models in market



from J. Grange, MiniBooNE data

- 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 Gev/c)
- Transverse enhancement model (TEM, Bodek et. al.), in the region where Nieves' model fails.

Ref. Guy Chanfray (Lyon)
talk for Martini model

All the models should be tested against the data, to know what's the nature's choice.

Transverse Enhancement Model

- This approach is motivated by the fact that the additional transverse cross-section is well-known in electron scattering.
- Parameterizes transverse enhancement as a modification to electromagnetic form factor.
- Provides a simple recipe to replace the dipole form-factor by a new one.

$$G_M^{p,n}(Q^2) -> (\sqrt{(1 + A \times Q^2 \times \exp(\frac{Q^2}{B}))})G_M^{p,n}(Q^2)$$

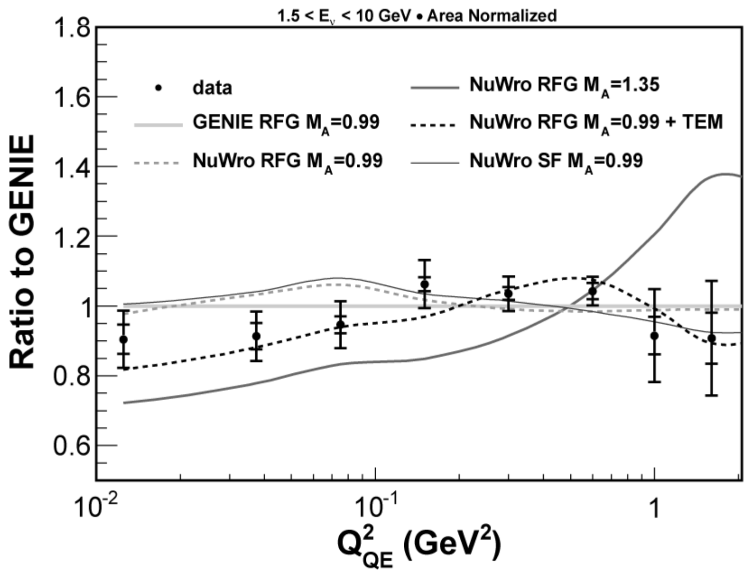
- Simple to implement.
- Matches fairly well at higher energies.
- Disadvantage : only gives lepton kinematics, not what the hadrons are doing.

arXiv:1106.0340

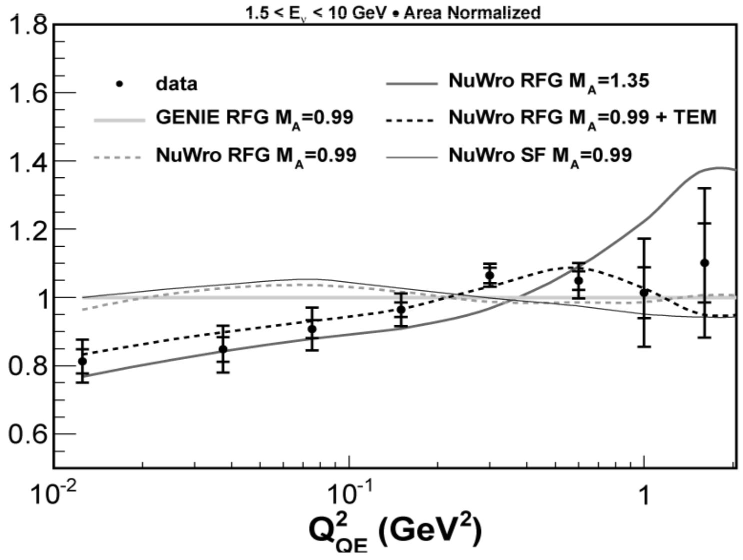
Validation by MINERνA

- Finely segmented scintillator detector to measure ν_μ & $\overline{\nu}_\mu$ QE interactions on nuclear targets.
- At energies between 1.5 and 10 GeV
- Plots below compare the cross-section from different nuclear models, taking ratio with GENIE expectation from nominal Ma value.

Neutrino



Antineutrinos



MINERνA cross-section results are in best agreement with a TEM with $M_a = 0.99$ GeV/c2 above 1.5 GeV.

10.1103/PhysRevLett.111.022502 / 022501

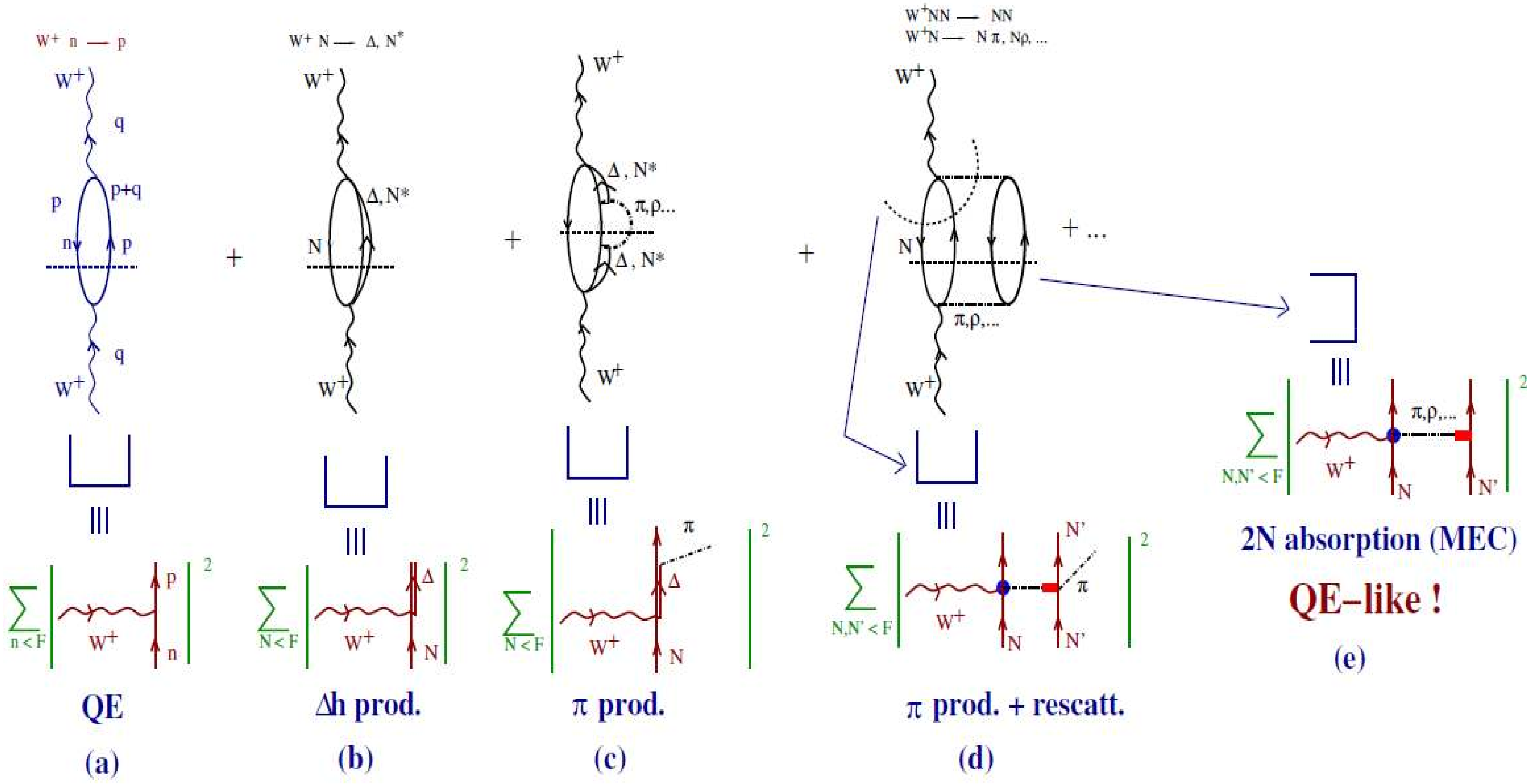
Nieves's multi-nucleon ejection model.

- Successfully tested on electron-nucleus scattering 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.

arXiv:nucl-th/0408005
arXiv:1307.8105

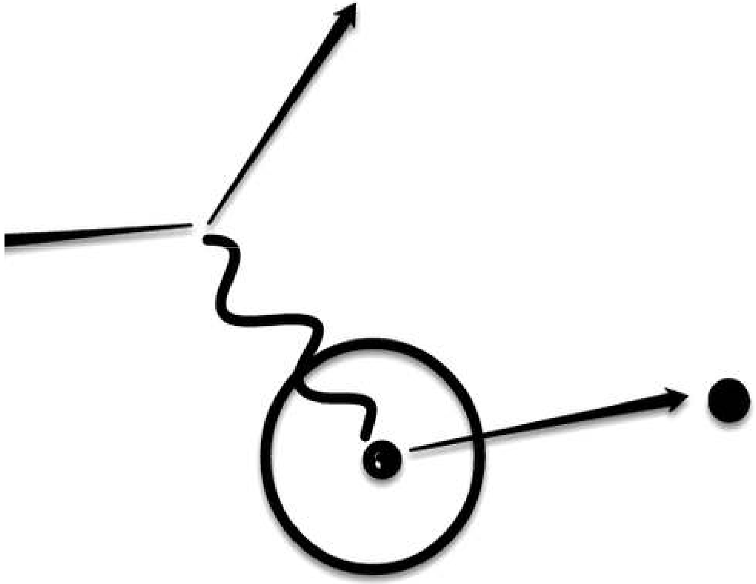
For formalism, talk by Horst Lenske (Giessen)
Meson production in coherent neutrino-nucleus reactions

Recipes for W-boson absorption.



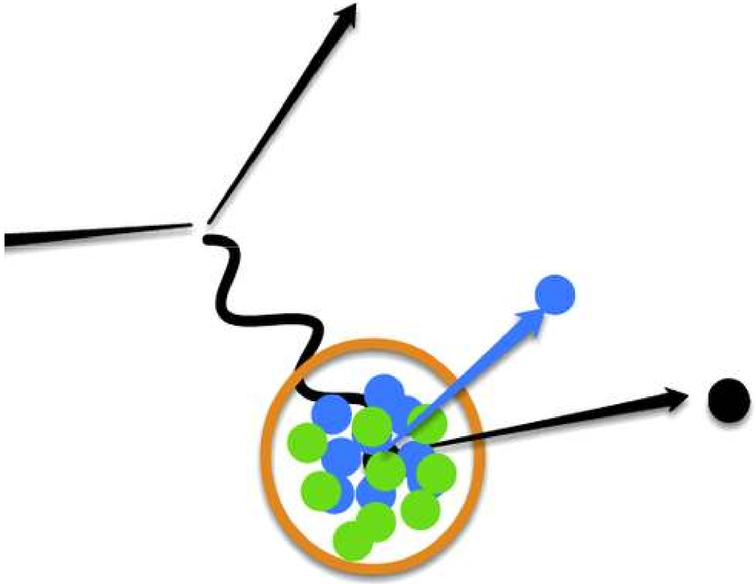
J. Nieves et.al

QE with Impulse Approximation



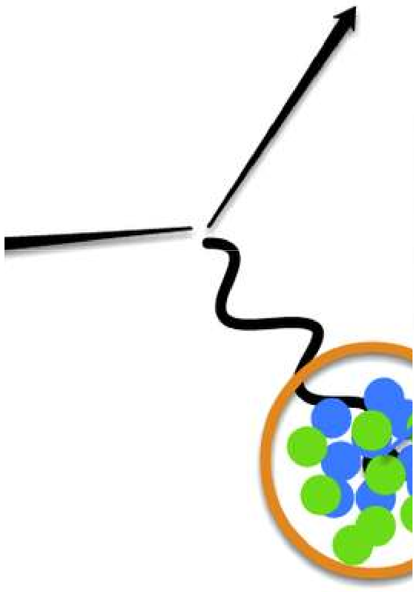
Cartoon illustration

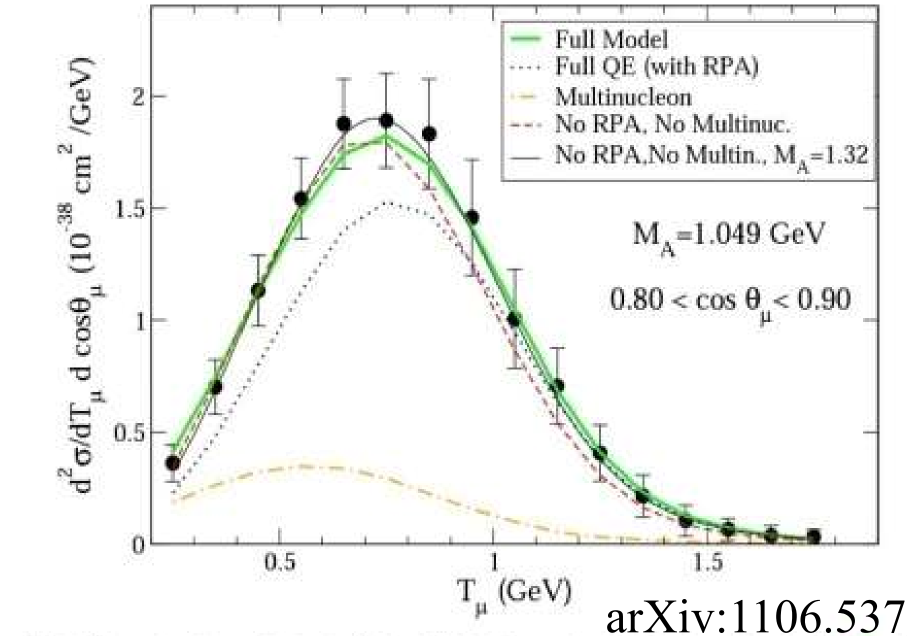
Multi-nucleon ejection mechanism



Cartoon illustration

Multi-nucleon Ejection mechanism

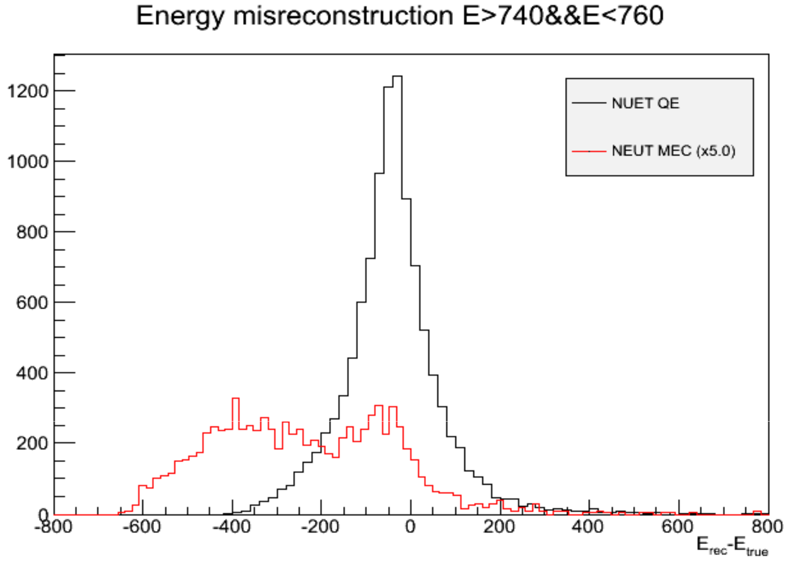




arXiv:1106.5374

Nieves's multinucleon model+ QE with RPA fits MiniBooNE data.

Concern for Oscillation Analysis



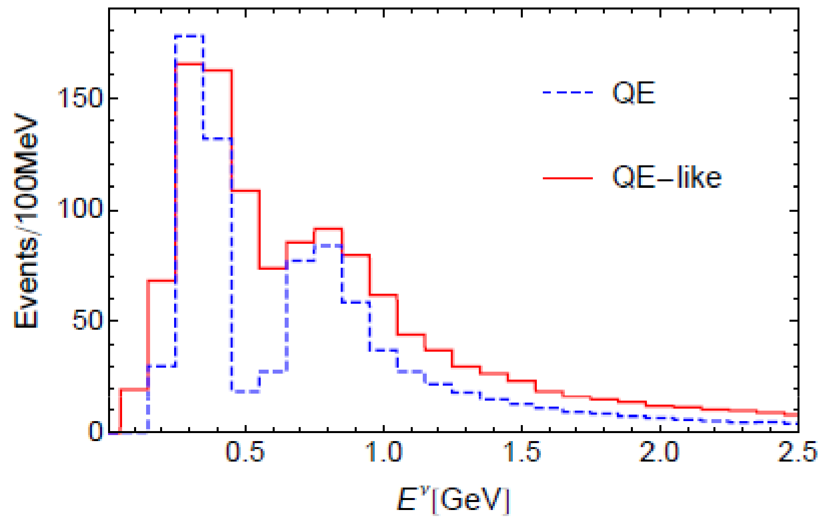
Black: only QE sample. Red : npnh events reconstructed as QE using formula given below

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

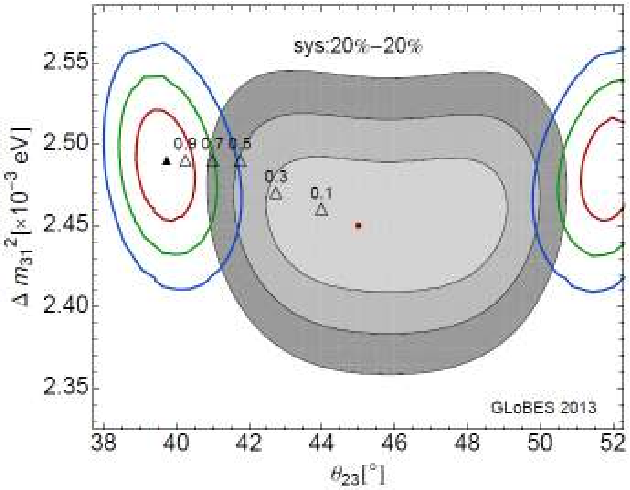
- Multi-nucleons interaction have different lepton kinematics than CCQE.
- If selected as CCQE sample and energy calculated using lepton kinematics, leads to **mis-reconstruction of neutrino energy.**
- Consequently affects oscillation analysis (E dependence of survival/oscillation probability.)

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

Bias on oscillation parameters



Impact of nuclear effects on the extraction of oscillation parameters.
P. Coloma and P. Huber



arXiv:1307.1243v1

Δ = 0 nuclear model completely known
Δ = 1 nuclear model completely ignored

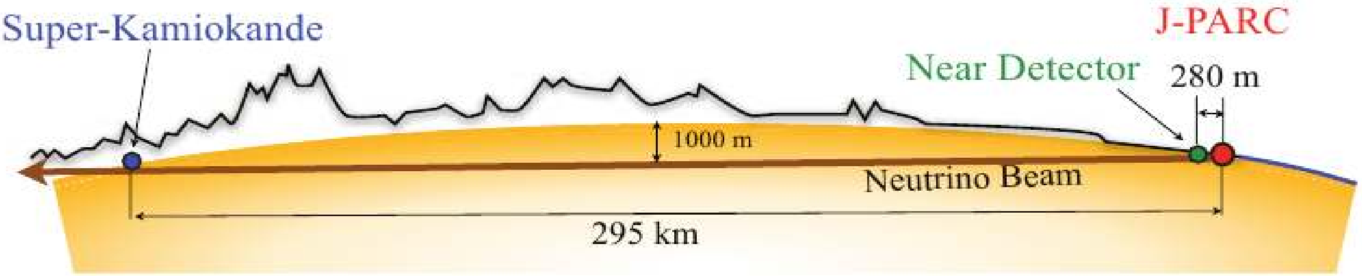
arXiv:1308.0465

T2K ν_μ studies:
An estimation of the bias on the oscillation parameters from these processes appears to be smaller than the current statistical precision when the overall rate of CC interactions with ND280 data is constrained and the uncertainties in pion-less Δ particle decay are included.

For more on importance nuclear effects on oscillation analysis refer talk by Ulrich Mosel (Giessen)

T2K - efforts

- For further precision measurement of oscillation parameters, systematics from nuclear effects will become significant as statistical errors reduce.
- In order to account for this, Nieves's multi-nucleon model is implemented in NEUT (official generator for T2K.) will be extended by TEM model in higher q3 space
- Studies are carried out to estimate the bias on OA from multi-nucleon models.
- In addition , other nuclear effects are also studied, like Spectral function model , single pion models and FSI models are modified in NEUT.



Talk on T2K physics program, Bruce Berger (Fort Collins) Sept. 23 , 9.00hr

Future perspective

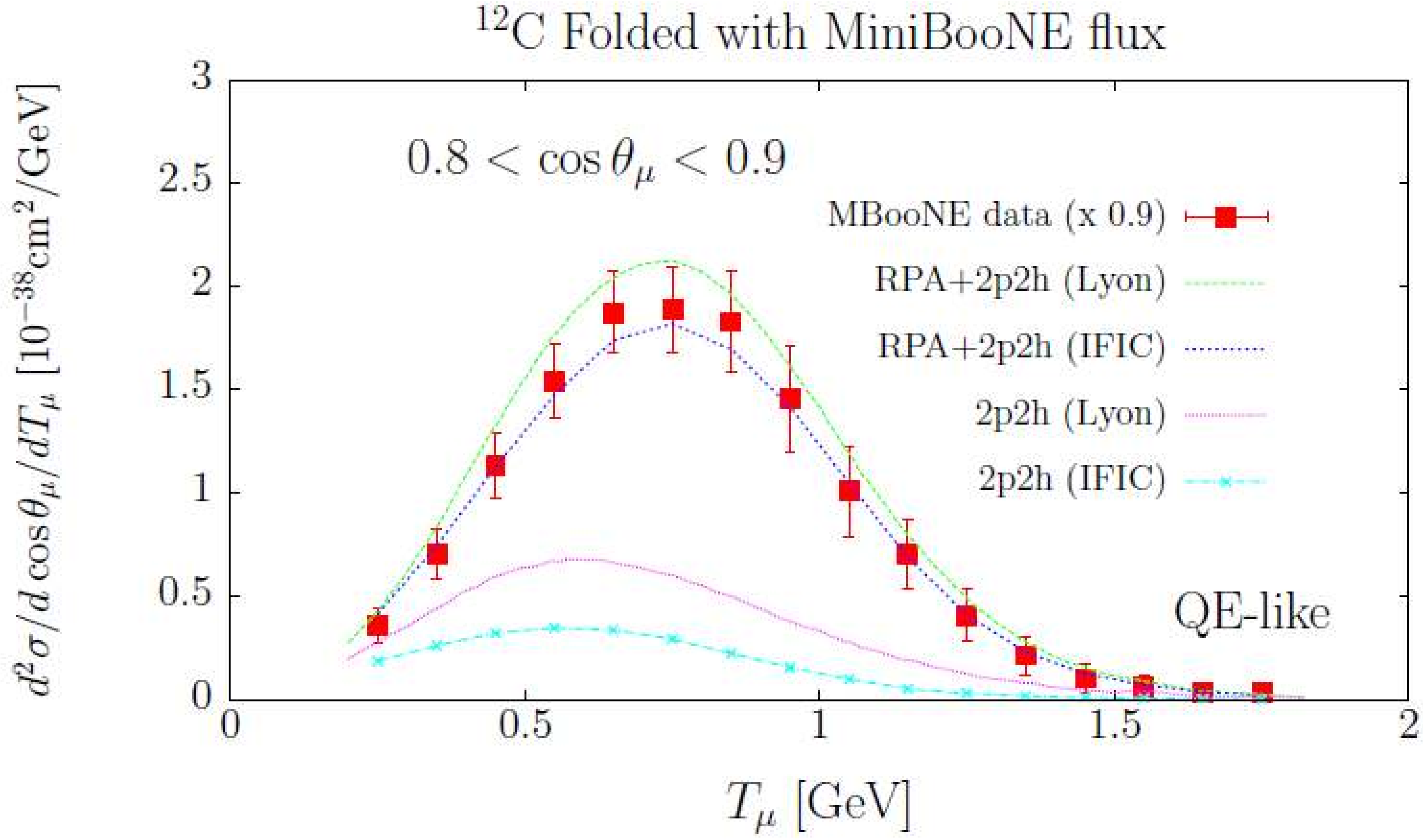
- Model Dependent:
  - Study systematic on oscillation analysis.
  - Using newly modified generators with multi-nucleon models implemented in it.

- Model Independent studies
  - With the realization of our ignorance in understanding nuclear effects in neutrino interaction, experiments are now encouraged to present unbiased model independent cross-section, which a theorist may use to test/refine their models.
  - In this approach one tries to quantify the excess seen as a function of lepton energy over nominal value of M_a.

Summary

- We confronted the cross-section discrepancy seen in MiniBooNE and recent cross-section measurement.
- These discrepancies could be answered by considering nuclear effects.
- We saw models that could answer QE cross-section discrepancy. Its effect on the oscillation measurements and need to address this in further analysis.
- Note: There are many other effects also to be considered to get a precise picture of the reality.
- But due to inherent difficulties is knowing the reality, efforts should be twofold. First test the models against the data from different experiment and look at the effects of validated models on other physics analysis.

Thank you



arXiv:1209.6586v1

Cross-section measurement

$$\sigma(E) = \frac{N_{\nu}^{QE}}{\Phi(E) \times T}$$

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

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

- **Increase the flux**
- Increase the energy ($\sigma_{\nu} \alpha E$). 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.