On measuring two-body current contribution to neutrino inclusive cross section

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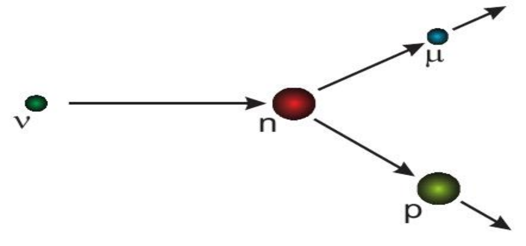
Outline

- Motivation
  - What is charge current quasi-elastic (CCQE) interaction?
  - Experimentalist definition of CCQE.
  - Axial mass puzzle; MiniBooNE 2D data.
  - Energy reconstruction (back-up slides).
- Two-body current - theoretical models.
- Multinucleon knock-out model.
- Two-body current - experimental aspects:
  - Two reconstructed knock-out protons.
  - Integrated knock-out proton kinetic energy.
  - Other approaches.
- Outlook.

Quasielastic reaction on a free nucleon target

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

$$\bar{\nu}_l + p \rightarrow l^+ + n.$$



Everything is clear. There are a muon and a proton in the final state.

Nuclear target reaction

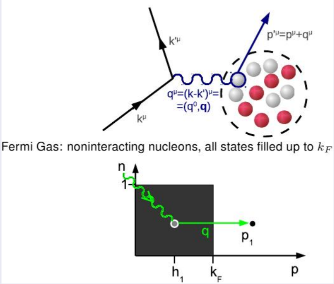
We would like to use the same definition in neutrino-nucleus reactions.

Complications:

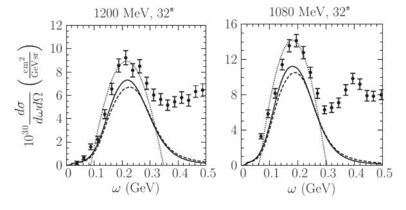
- Can we assume that neutrino *sees* nucleus as composed of quasi-free nucleons (validity of impulse approximation (IA))?...
- What is an experimental *definition* of CCQE? A muon and a proton in the final state, as before (impact of final state interaction (FSI) effects)?...

Impulse approximation – Fermi gas model

In the IA we assume that nucleons are quasi-free like in Fermi gas model. Correct?...



from Jakub Zmuda

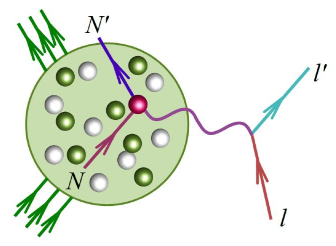


from A. Ankowski, JTS, Phys. Rev C77 (2008) 044311

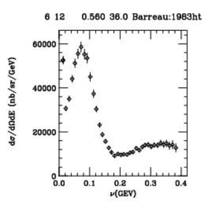
Electron scattering: In wide kinematical region IA works quite well.

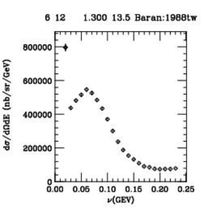
Electron energy and scattering angle are fixed.

Impulse Approximation (IA) - limitations



from Artur Ankowski





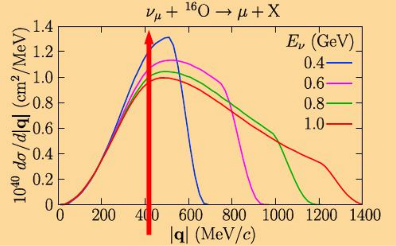
Electron carbon data

Think about de Broglie wave and remember 1 fm $\sim$ (200 MeV)$^{-1}$. If momentum transfer is 200 MeV spatial resolution is 1 fm. If momentum transfer is smaller than $\sim$ 300 MeV IA becomes problematic.

In fact, for small energy transfers one can see giant resonances.

Impulse approximation (IA) - limitations

In electron scattering one can select a kinematical region in which IA is reliable.
In neutrino experiments beams are always rather wide-band and above is impossible. How much of the cross section come from the low momentum transfer region?



from Artur Ankowski

Usually Q^2 is used, where $Q^2 = q^2 - \omega^2 \geq 0$. Low $|\vec{q}|$ translates to low Q^2.
There are always many "CCQE" events with small q (or Q^2).

Remedy: include RPA, or better CRPA, corrections.

How do experimentalists define CCQE?

MiniBooNE

- Only 2 *subevents* (Cherenkov light from muon and then from electron).
- No assumptions about proton.
- Most of CC events with pions give rise to 3 subevents.

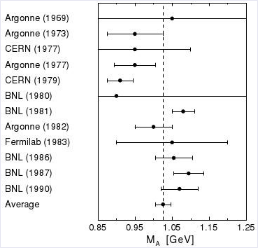
NOMAD

- 1- and 2-track events (muons and protons with $p > 300$ MeV/c).
- Several cuts are imposed to eliminate the (pion) background.

Do MiniBooNE and NOMAD measure the same?!...

CCQE axial mass puzzle

In a basic theory of CCQE the only unknown quantity is M_A, axial mass,
Until a few years ago it seemed that M_A measurements converge to a value $M_A \sim 1.03$ GeV.
There is a tension between old, mainly deuterium (left), and recent heavier target (right) M_A measurements.

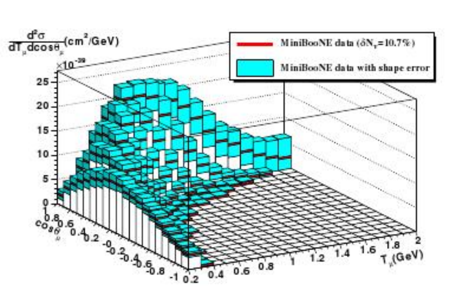


[from Bernard, Elouadrhiri, Meissner]

Experiment	Target	Cut in Q^2 [GeV^2]	M_A [GeV]
K2K[5]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[6]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[7]	iron	no cut	1.19 ± 0.17
MINOS[7]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[1]	carbon	no cut	1.35 ± 0.17
MiniBooNE[1]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

MiniBooNE double differential cross section data

The most interesting recent CCQE data comes from the MiniBooNE experiment.
The data is available in a form of double differential cross section in muon: kinetic energy and production angle:



A.A. Aguilar-Arevalo et al.,[MiniBooNE collaboration] Phys. Rev. D81, 092005 (2010)

The best fit value is $M_A^{eff} = 1.35 \pm 0.17$ GeV, $\kappa = 1.007 \pm 0.012$ (to cure low Q^2 problem).

Similar values of M_A^{eff} were obtained from shape only and normalized cross section analysis.

Effective axial mass?!...

It is a fit in a particular experimental situation (flux, detector, selection of events,...).
We need more universal description of the data, **we need a theory**.

What is there in the MB signal?

Background events come mostly from pion absorption. This background is subtracted from the CCQE-like sample of events.

NUANCE (Monte Carlo (MC) event generator used by MiniBooNE) assumes certain fraction of pionless Δ decays and such (MC) events are also subtracted (a very confusing point).

Hypothesis: there is a large two-body current multinucleon knock-out contribution to the inclusive CC cross section.

Two-body current – basic intuition

One-body hadronic current operator:

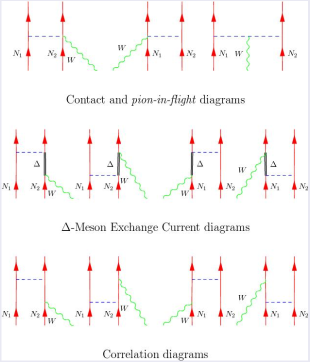
$$J^\alpha = \cos\theta_C (V^\alpha - A^\alpha) = \cos\theta_C \bar{\psi}(p')\Gamma^\alpha_V \psi(p)$$

In the second quantization language J^α is the operator which annihilates (removes from the Fermi see, producing a hole) a nucleon with momentum p, and creates (above the Fermi level) a nucleon with momentum p':

$$J^\alpha_{1body} \sim a^\dagger(p')a(p)$$

Two-body current – basic intuition

Think about more complicated Feynman diagrams:



Contact and *pion-in-flight* diagrams

Δ-Meson Exchange Current diagrams

Correlation diagrams

$$J^{\alpha}_{2body} \sim a^{\dagger}(p_1')a^{\dagger}(p_2')a(p_1)a(p_2)$$

can create two particles and two holes (2p-2h).

Microscopic models

- M. Martini, M. Ericson, G. Chanfray, J. Marteau (MEChM – based on Marteau PhD thesis $\sim$ 2000)
- J. Nieves, I. Ruiz-Simo, M.J. Vicente-Vacas
- J.E. Amaro, M.B. Barbaro, J.A. Cabbalero, T.W. Donnelly, C.F. Williamson, J.M. Udias

The models provide muon inclusive 2D cross section and a seperate problem is to get predictions for final state nucleons.

Effective models

- Bodek, et al
- Lalakulich, Mosel, et al model
- Steve Dytman model in GENIE.

Some comments

- There are large differences between the theoretical models predictions, by a factor of 2.
- There a controversy how large is two-body contribution in antineutrino scattering.
- Nieves et al stress a role of RPA effects: they must be included in order to reproduce the MiniBooNE data.
- There is an intriguing result of Carlson et al: for light nuclei in order to get observed (in the electron scattering) two-body current contribution one must use more realistic ground state than Fermi gas model (used in all the neutrino microscopic models...).

Terminology

Meson exchange current (MEC)

$\Updownarrow$

two-body current

$\Updownarrow$

n particles n holes ($np - nh$)

However, sometimes the term *MEC* refers only to a smaller subset of *two-body current* Feynman diagrams which lead to *np-nh* final states.

How to distinguish CCQE and two-body current events?

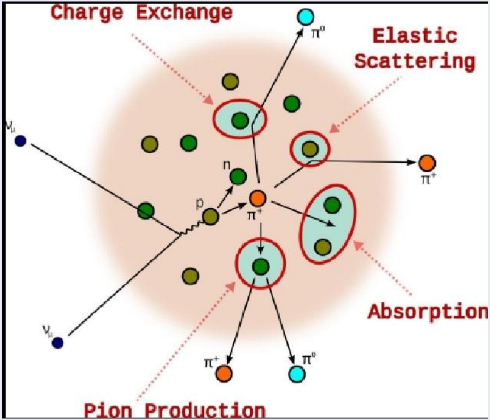
It is not enough to study muons.

One must analyze nucleons in the final state.

For that one needs theoretical predictions.

FSI effects are very important and a model giving predictions for nucleons after MEC events must be combined with a MC event generator (or hadronic transport code like GiBUU).

Relevance of Final State Interactions



from Tomasz Golan.

The cartoon is for pions, but analogous effects are experienced by nucleons.

The model

Based on JTS, arXiv:1201.3673[hep-ph]; to be published in Phys. Rev C.

A main idea: use as an input any model which gives predictions for the two-body contribution to the muon inclusive cross section and make predictions for the final state nucleons.

Two such muon scattering models will be used in numerical computations:

- Bodek et al TE model
- Marteau inspired model, not exactly the MEChM model, but similar in many respects

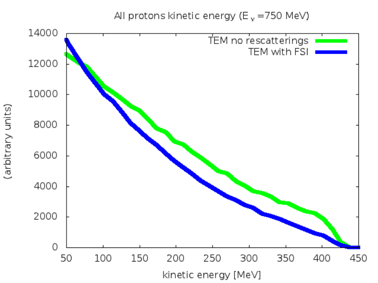
Both models are implemented in NuWro MC event generator.

The model of the nucleon knock-out

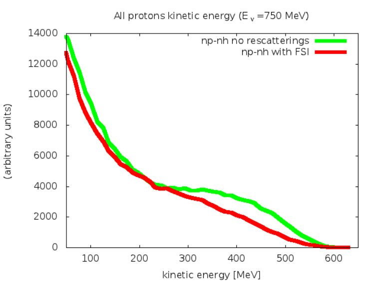
We use only muon information.

- We know muon's kinetic energy and production angle.
- Equivalently, we know momentum and energy transfer.
- We select 2(3) nucleons from the Fermi see.
- We add the energy and momentum transfered to the hadronic system.
- We perform a boost to the hadronic center-of-mass frame (CMF).
- In the CMF we select isotropically 2(3) nucleons in the final state.
- We perform boost back to the laboratory frame.
- Energy balance must be consistent with FSI model.
- Event's weight is given by muon differential cross section.

Predictions – relevence of FSI effects (1)



Effective transverse enhancement model.

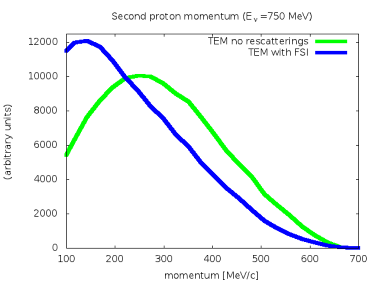


Microscopic model.

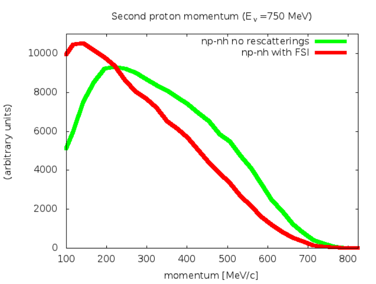
Predictions from two models implemented in NuWro are compared.

Due to FSI effects protons become less energetic.

Predictions – relevence of FSI effects (2)



Effective transverse enhancement model.



Microscopic model.

If the second proton is energetic enough we can see a pair of protons in one event.

The second energetic proton can has quite large momentum!

How to measure the two-body current contribution?

- Of interest are CCQE-like events, with no pions in the final state; one needs a strong veto on pions.
- One can use the information contained in reconstructed proton tracks and also in the *vertex activity*.
- It is better to have a low threshold for reconstruction proton tracks.
- The quality of FSI model is very important, real pion absorption seems to be the most important background.
- Observables like integrated kinetic energy seem to be less affected by FSI.

IDEA 1: Pairs of reconstructed knocked-out protons

TE model. Predicted number of proton pairs with both momenta above various threshold values and two threshold values of the $\pi^{\pm}$ momentum. Simulations done for the 750MeV muon neutrinos. The number of generated events is $2.5 \cdot 10^5$.

$\pi^{\pm}$ cut $[\frac{MeV}{c}]\downarrow$	proton cut $[\frac{MeV}{c}] \rightarrow$	300	400	500
0	signal	5457	2271	651
	background	13780	7961	2267
200	signal	5465	2271	651
	background	16112	8691	2349

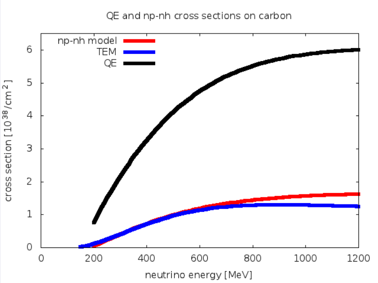
IDEA 1: Pairs of reconstructed knocked-out protons

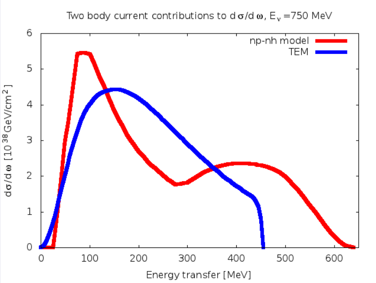
Microscopic model. Predicted number of proton pairs with both momenta above various threshold values and two threshold values of the $\pi^{\pm}$ momentum. Simulations done for the 750MeV muon neutrinos. The number of generated events is $2.5 \cdot 10^5$.

$\pi^{\pm}$ cut $[\frac{MeV}{c}]\downarrow$	proton cut $[\frac{MeV}{c}] \rightarrow$	300	400	500
0	signal	7185	4201	1805
	background	13774	7928	2311
200	signal	7231	4201	1805
	background	16158	8577	2388

IDEA 1: Pairs of reconstructed knocked-out protons

Model predictions for the proton pairs above 500 MeV/c signal differ by a factor of 3. Why?

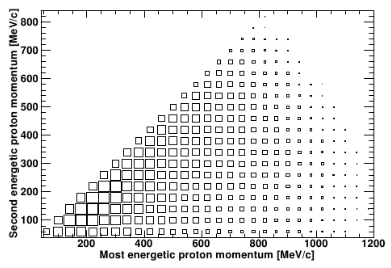




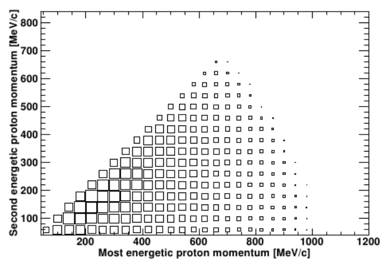
In the microscopic model typical energy transfers are larger which translates into more energetic protons.

IDEA 1: Pairs of reconstructed knocked-out protons

Of interest can be also 2D distributions of two most energetic protons:



Microscopic model.



TE model.

IDEA 1: Pairs of reconstructed knocked-out protons; resumé

A probability to have an event with two protons above 500 MeV/c is 0.26...0.72%. For a 400 MeV/c threshold a probability is 0.9...1.7%,

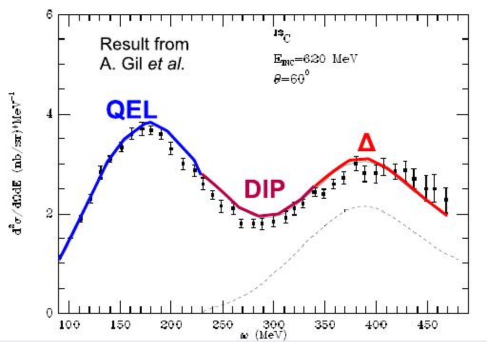
For the 500 MeC/c threshold signal/background ratio is 0.28 ... 0.75.

Which is an uncertainty in NuWro background estimation? For E=1 GeV a comparison with GENIE: an agreement is within 30-50% (GENIE predicts the background to be smaller)

I thank Steve Dytman for providing me results of GENIE simulations.

IDEA 2: Integrated knocked-out protons kinetic energy

Two-body current events are believed to populate a DIP region between QE and Δ peaks:



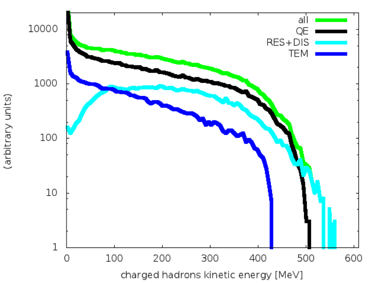
A. Gil, J. Nieves and E. Oset, Nucl. Phys. A 627 (1997) 543;

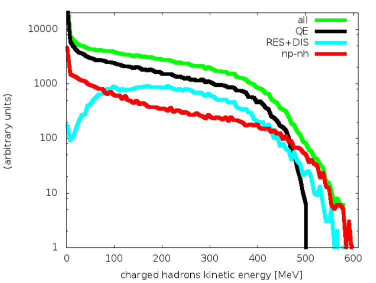
IDEA 2: Integrated knocked-out protons kinetic energy

Define two observables: $\sum_j T_j$ and $\frac{\sum_j T_j}{E_\mu}$, where T_j is the kinetic energy of charged hadron. We include all the kinetic energy: both reconstructed hadrons and blobs.

Assume, all π^0 and $\pi^\pm$ with momenta above 200 MeV/c are detected. Events with detected pions are not included in the analysis.

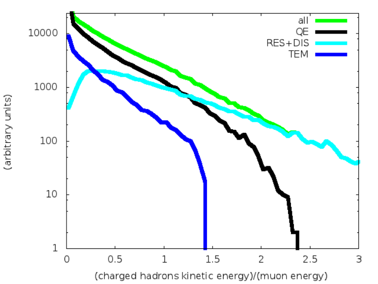
IDEA 2: Integrated knocked-out protons kinetic energy

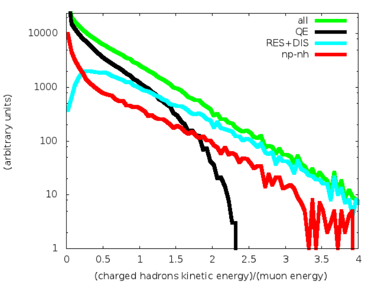




Various dynamical mechanisms contribute with different shapes. From the measured shape one can try to deduce existence of the MEC contribution.

IDEA 2: Integrated knocked-out protons kinetic energy

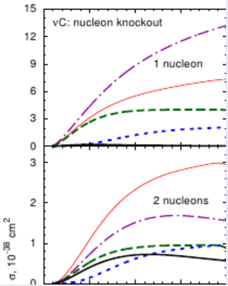


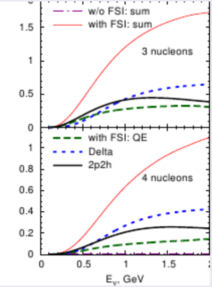


Muon energy sets energy scale of an event. From the measured shape one can try to deduce existence of the MEC contribution.

Other approaches (1)

Until now, we discussed a model described in arXiv:1201.3673. The same problem is discussed by Lalakulich, Gallmeister, Mosel, arXiv:1203.2935.

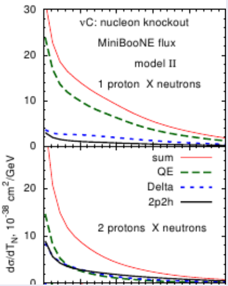


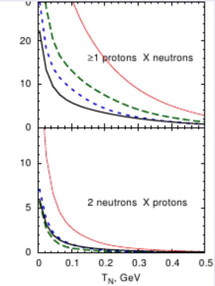


2p2h contributes to 2,3,4 nucleon knock-out, but there are also large contributions from QE (due to FSI) and Δ.

Other approaches (2)

Which are energies of knocked-out nucleons?





For 2 protons probably a sum of kinetic energies of protons/nucleons is shown.

It is very difficult to compare models predictions because results are given in different formats.

Outlook

- During last three years (since NuInt09 in Sitges) there has been a lot of discussions about two-body current contribution to muon inclusive cross section.
- Theorists proposed various models.
- It is time to try to measure the effect by looking at final state nucleons.
  - In some models (Martini et al) the contribution is really large.
  - The task is not easy and requires reliable simulation tools to describe nucleon propagation in nuclear matter.

But still...

- ... hopefully, there is a chance to see the effect or at least to put constraints on theoretical models.

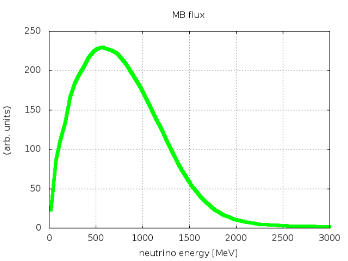
Thank you for your attention!

Energy reconstruction (1)

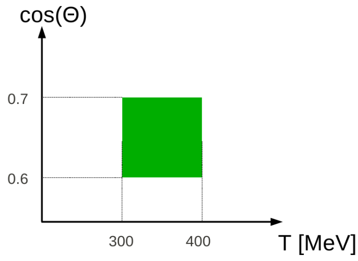
If one infers about neutrino energy based on an detected muon only, MEC events introduce a bias.

A case study. Consider only CCQE and MEC events.

Consider MiniBooNE neutrino flux...



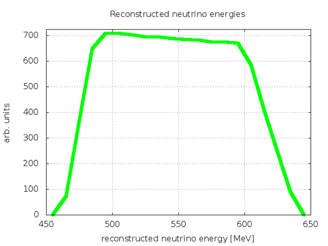
... and a particular 2D muon bin



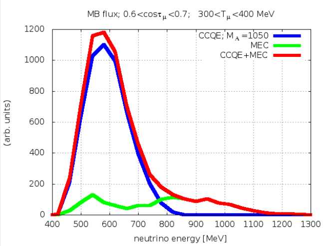
Energy reconstruction (2)

Then...

... neutrino energies calculated using a standard reconstruction formula are:



... while true neutrino energies are:



Notice a large true neutrino energy tail coming from the two-body current contribution.

From J. Morfin, JTS, poster presented at NEUTRINO 2012.

Energy reconstruction

The problem of neutrino energy reconstruction is studied in detail in:

M. Martini, M. Ericson, G. Chanfray, Phys.Rev. D**85** (2012) 093012.

O. Lalakulich, K. Gallmeister, U. Mosel, *Many-Body Interactions of Neutrinos with Nuclei - Observables*, arXiv:1203.2935 [nucl-th].

D. Meloni, M. Martini, *Revisiting the T2K data using different models for the neutrino-nucleus cross sections*, arXiv:1203.3335 [hep-ph].

J. Nieves, F. Sanchez, I. Ruiz Simo, M.J. Vicente Vacas, *Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section*, arXiv:1204.5404.