# Two body current contribution to neutrino inclusive cross section

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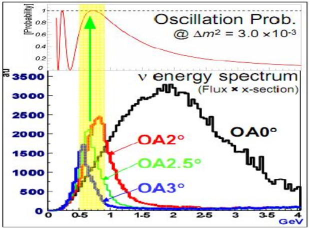
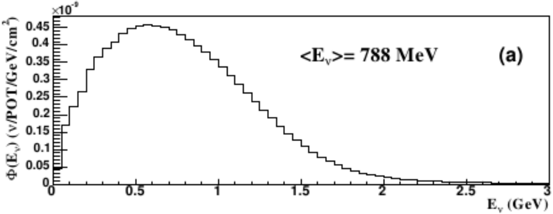
Outline:

- introduction, neutrino interactions
- two body current contribution
- how to measure the effect?
  - general remarks
  - NuWro
  - MINERvA
  - final state interactions effects
- conclusions

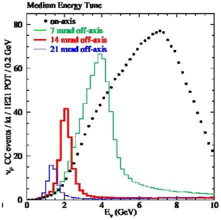
A focus on 1 GeV energy region:




T2K flux (many years of collaboration with Ewa Rondio, Danka Kiełczewska and others in T2K experiment)



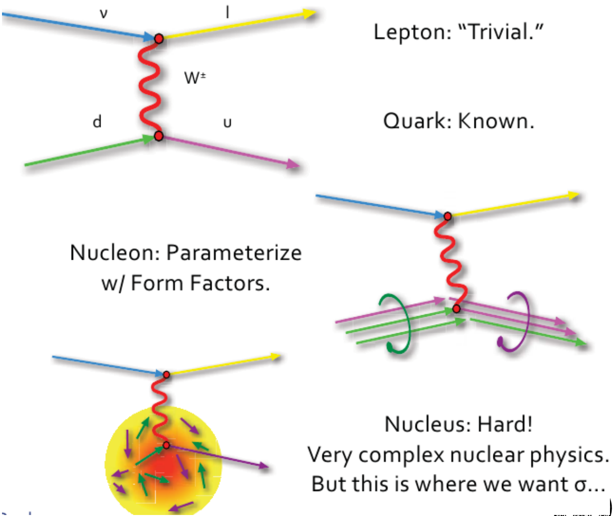

MiniBooNE flux




NOvA flux

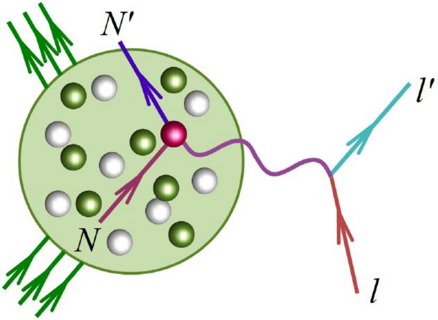
Purely leptonic interactions are exactly known in Standard Model (unfortunately, only a minor fraction of the cross section at $\sim 1$ GeV)

Big majority of interactions occur on bound states (nucleons, nuclei) with many complications.




(from G. Purdue)

Until recently 1 GeV neutrino interactions were discussed always in the **impulse approximation** (IA) picture: neutrinos interact with individual bound nucleons.

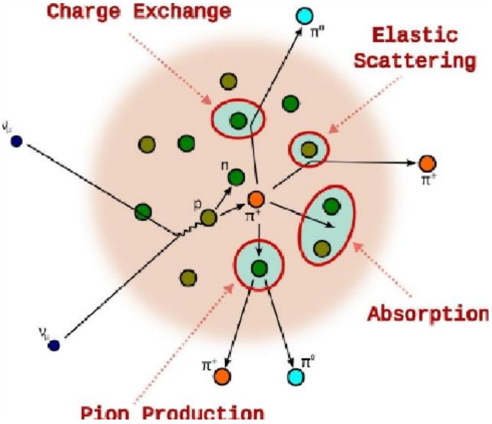



from Artur Ankowski

Within the IA one needs a distribution of momenta and binding energies of target nucleons.

$\nu$ nucleus interaction is a two-step process: a primary interaction followed by final state interactions (FSI) effects: before leaving nucleus hadrons undergo reinteractions.

# Final state interactions:

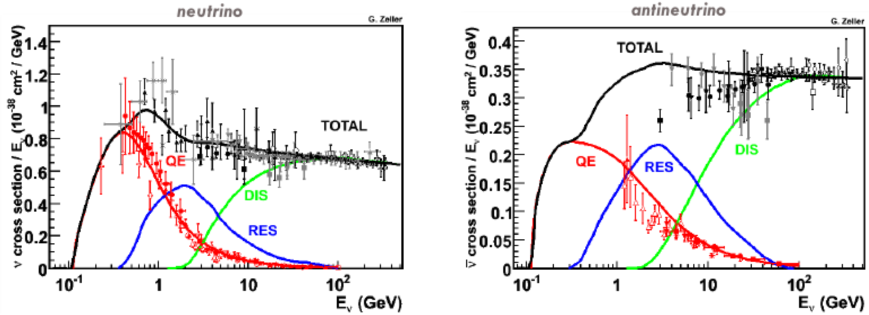



(from T. Golan)

Pions...

- can be absorbed
- can be scattered elastically
- (if energetically enough) can produce new pions
- can exchange electic charge with nucleons

Big picture.




(from Sam Zeller; based on P. Lipari et al, Phys. Rev. Lett. 74 (1995) 4384)

CCQE is $\nu_\mu \; n \to \mu^- \; p$, or $\bar{\nu}_\mu \; p \to \mu^+ \; n$.

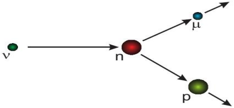
RES stands for resonance region e.g. $\nu_\mu \; p \to \mu^- \; \Delta^{++} \to \mu^- \; p \; \pi^+$;
one often speaks about SPP - single pion production

DIS stands for: more inelastic than RES.

# CCQE

The most abundant reaction in T2K:

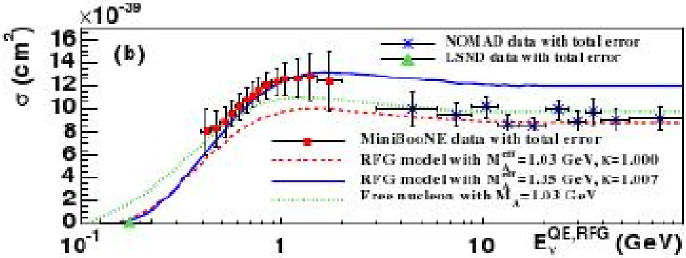
$$\nu_l(k) + n(p) \to l^-(k') + p(p')$$




In case of free target reaction an experimental signal would be clear: muon and proton in the final state.

- the only unknown quantity is $M_A$, axial mass,
- from pion electroproduction $M_A = 1.077 \pm 0.039$ GeV.
- $M_A$ determines both the overall integrated cross section and the shape of $\frac{d\sigma}{dQ^2}$,
- several recent CCQE measurements: much larger $M_A$?!

The most important is the high statistics MiniBooNE CCQE measurement published in a form of (muon) double differential cross section.




There is a tension between MiniBooNE and NOMAD (also mostly Carbon target but larger energies) CCQE measurements.

CCQE kinematics does not depend much on neutrino energy due to $Q^2$ cut-off in form factors.

## How do experimentalists define CCQE?

### QE reaction on nuclear target - 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

### QE reaction on nuclear target - 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?!...

There are many indications that there is a large multinucleon knock-out contribution contained in the MB CCQE signal and probably (nobody investigated that really!) not included in the NOMAD's selection of CCQE events.

## What is there in the MB signal? (cont)

- 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 $\Delta$ decays and such (MC) events are also subtracted (a very confusing point),

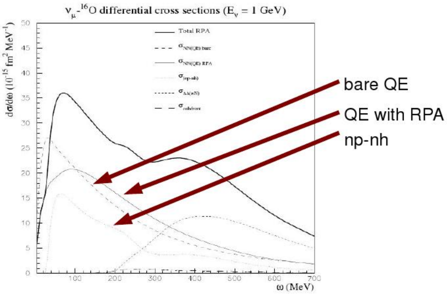
## MiniBooNE experiment suggested *effective axial mass* $M_A^{eff} = 1.35$ GeV

- 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**.

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

## Marteau model

The figure below is taken from the Jacques Marteau seminar given... 11 years ago at NuInt01.



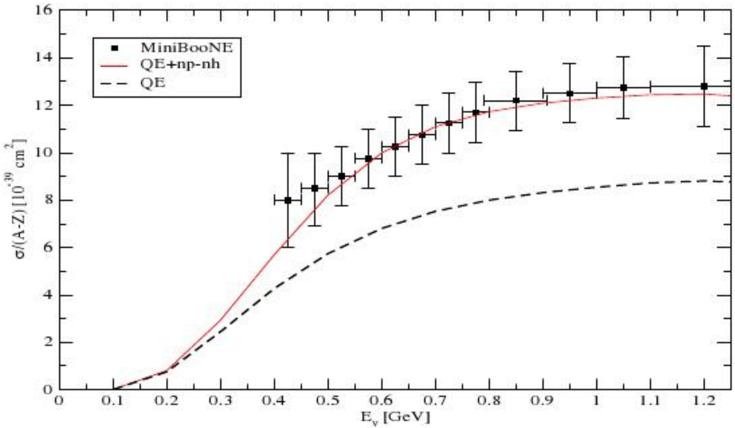

$\sim$ a half of *bare QE* part!

The original idea was put forward by Magda Ericson in 1990: appearance of pion branch, a collective state which decays into a pair of nucleons.

The model developed by J. Marteau in his PhD thesis (1998) supervised by J. Delorme predicts a large contribution from n-particle n-hole excitations.

The model was almost forgotten for $\sim$ 8 years and reintroduced to the community by Marco Martini. Danka Kiełczewska was always telling me: study the Marteau model!

## Martini model and the MiniBooNE data




GREAT!

Terminology:

for a purpose of this talk

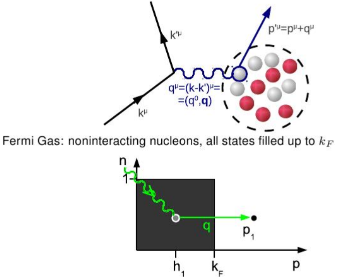
Meson exchange current (MEC)
$\Updownarrow$
two body current
$\Updownarrow$
n particles n holes ($np-nh$)

(in general the term *MEC* refers to a smaller subset of the *two body current* diagrams which lead to *np-nh* final states)

# Two-body current – basic intuition.

One-body hadronic current operator:

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



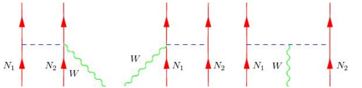

from Jakub Zmuda

In the second quantization language $J^\alpha$ 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':

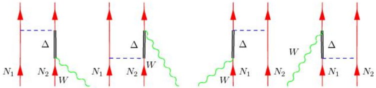
$$J^\alpha_{1body} \sim a^\dagger(p')a(p)$$

## Two-body current – basic intuition

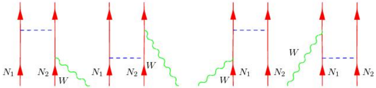
Think about more complicated Feynman diagrams:




Contact and *pion-in-flight* diagrams




Δ-Meson Exchange Current diagrams




Correlation diagrams

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

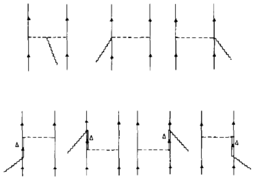
can create two particles and two holes (2p-2h).

# Two body current

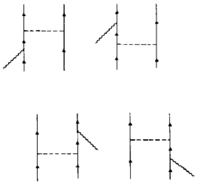
In the electron scattering community nothing new

Typical expresion for non-relativistic current operator (pion in flight)

$$\mathbf{J}^{\pi}(\mathbf{p}_1' - \mathbf{p}_1, \mathbf{p}_2' - \mathbf{p}_2) = -\frac{4M^2c^4}{V^2\hbar c}\frac{f_\pi^2}{\mu_\pi^2}\chi_{s_1'}^{+}\frac{\boldsymbol{\sigma}\cdot\mathbf{k}_1}{k_1^2+\mu_\pi^2}\chi_{s_1}\chi_{s_2'}^{+}\frac{\boldsymbol{\sigma}\cdot\mathbf{k}_2}{k_2^2+\mu_\pi^2}\chi_{s_2} \times (\mathbf{k}_2 - \mathbf{k}_1)\, 4\rho_1 \cdot \mathscr{F}_E$$

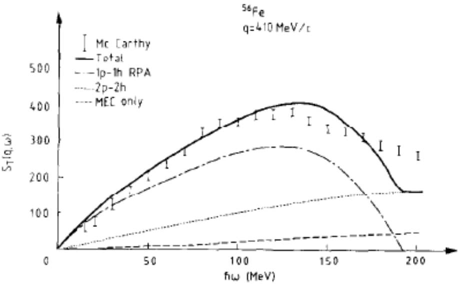



MEC diagrams



correlation diagrams

from Alberico, Ericson, Molinari, 1984

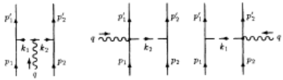


# Relativistic computations:

$$\mathcal{L} = \overline{\psi}_N (i\partial\!\!\!/ - M)\psi_N + \tfrac{1}{2}(\partial_\mu \boldsymbol{\phi}\cdot\partial^\mu\boldsymbol{\phi} - m_\pi^2 \boldsymbol{\phi}\cdot\boldsymbol{\phi}) + \frac{g_\pi}{2M}\overline{\psi}_N\, i\partial\!\!\!/\boldsymbol{\phi}\,\gamma^5\psi_N\cdot\boldsymbol{\tau},$$

$$W^{\mu\nu}_{\mathrm{2p2h}} = \sum_{\mathrm{2p2h}} \langle \mathrm{FG}|J^{\dagger\nu}_{(2)}|\mathrm{2p2h}\rangle\langle\mathrm{2p2h}|J^{\mu}_{(2)}|\mathrm{FG}\rangle,$$

$$\partial_\mu \to \partial_\mu + ieA_\mu$$



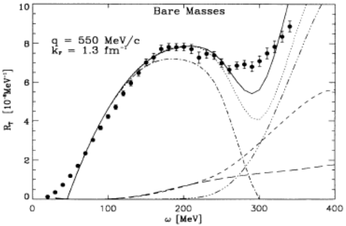
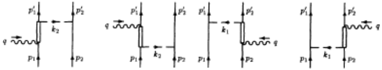



FIG. 15. Comparison of the combined transverse response (solid line) of the quasifree knockout (dash-dotted line), the pion production (dash-triple dotted line) and the full two-body knockout (dashed line) with the data of kinematics I for $^{56}$Fe. Also displayed is the static-limit result for the two-body knockout contribution (long-dashed line). Finally, the dotted line shows the combined response one would obtain replacing the full two-body results with the SL two-body results. The data are taken from [5].

$$\mathcal{L}_{\pi N\Delta} = \frac{if_{\pi N\Delta}}{m_\pi}\bar{\psi}^\mu_\Delta(4g_{\mu\nu} - \gamma_\mu\gamma_\nu)\mathbf{T}^\dagger\psi_N\partial^\nu\cdot\boldsymbol{\phi} + \mathrm{H.c.}$$

$$\Delta\to\gamma N: \quad \frac{f_{\gamma N\Delta}}{2M}(q\!\!\!/ g^{\mu\nu} - \gamma^\mu q^\nu - \tfrac{1}{2}iq_\alpha\sigma^{\alpha\mu}\gamma^\nu)\gamma^5 T^3$$
$$\equiv \frac{f_{\gamma N\Delta}}{2M}\mathcal{G}^{\mu\nu}T^3, \qquad (3.15)$$
$$\gamma N\to\Delta: \quad \frac{f_{\gamma N\Delta}}{2M}(q\!\!\!/ g^{\mu\nu} - \gamma^\mu q^\nu + \tfrac{1}{2}iq_\alpha\gamma^\nu\sigma^{\alpha\mu})\gamma^5(T^\dagger)^3.$$



Dekker, Brussaard, and Tjon, Phys. Rev. C49 (1994) 2650

# Theoretical models:

Microscopic approaches:

- M. Martini, M. Ericson, G. Chanfray, J. Marteau (MEChM – based on the Marteau papers, developed by Martini)
- 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

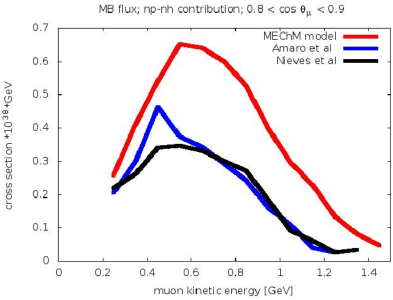
Effective models:

- A. Bodek, et al – transverse enhancement
- U. Mosel et al model for GiBUU (constant transition matrix element)
- S. Dytman model in GENIE

A model of A. Meucci and C. Giusti.

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

## Microscopic multinucleon knock out models




- many similarities between IFIC and Lyon models
- Lyon model relies on electron scattering computations, *extrapolated* to axial and axial-vector contributions
- similar $\Delta$ self-energy contribution
- superscaling approach (Amaro et al) relies on empirical $(e, e')$ scaling function

All the computations rely on the Fermi gas model. More realistic computations are very difficult.

How much should we care about MEC contribution? Is that relevant if an interaction was QE or MEC?

It is important for our understanding of interacting $\nu$ energy.

Notation: four-vectors of $\nu$, $\mu^-$, neutron and proton are denoted as:
$k^\mu = (E_\nu, \vec{k})$, $k'^\mu = (E', \vec{k}')$, $p^\mu = (M, \vec{0})$, $p'^\mu = (E_{p'}, \vec{p}')$.

If only final state muon is detected, $E_\nu$ can be evaluated assuming target neutron was at rest and the interaction was QE:
Energy and momentum conservation ($B$ is a binding energy, $m$ is charged lepton mass, $M$ is nucleon mass):
$E_\nu + M - B = E' + E_{p'} \qquad \vec{k} = \vec{k}' + \vec{p}'$

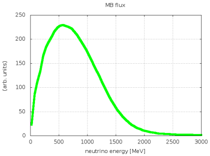
$$E_{p'}^2 = M^2 + \vec{p}'^2 = M^2 + (\vec{k} - \vec{k}')^2 = M^2 + E_\nu^2 + \vec{k}'^2 - 2E_\nu|\vec{k}'|\cos\theta.$$

$$E_{p'}^2 = (E_\nu - E' + M - B)^2.$$

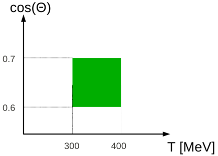
Neglecting a difference between proton and neuton mass we obtain:

$$E_\nu = \frac{E'(M-B) + B(M-B/2) - m^2/2}{M - B - E' + k'\cos\theta}.$$

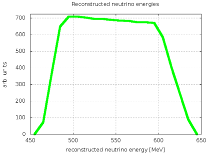
MEC events are suspected to introduce a strong bias to energy reconstruction.



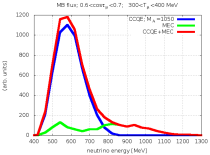

Consider MB flux...




... and a particular 2D bin.




$E_{rec}$ using CCQE formula.

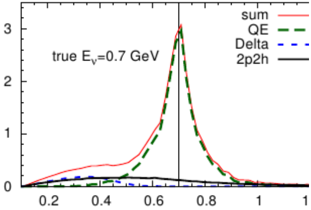



$E_{true}$ from CCQE and MEC events.

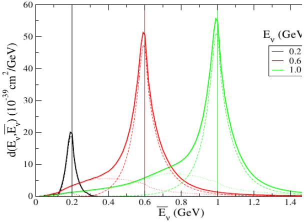
On the bottom right: a tail from MEC events: $\nu$ energy is underestimated.

[from J. Morfin, JTS, poster presented at NEUTRINO 2012, Kyoto].

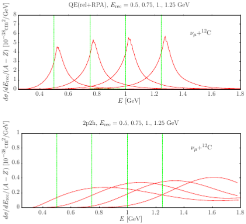
There is a lot of theoretical discussion on the impact of MEC on $\nu$ energy recontruction, with similar conclusions:




Mosel and Lalalukich




Martini et al




Nieves and Sanchez

Recent T2K studies indicate that the effect of MEC is not that dangerous:

- NEUT simulates pionless $\Delta$ decays which is a substantial part of the effect in the Nieves model
- ND280 information is used.

A unique way to separate MEC from CCQE is to analyze final state nucleons.

- a lot of information is lost because of FSI effects
- one should use information in reconstructed tracks and also in *vertex activity*
- it is important to have a strong veto on pions

Monte Carlo implementation is necessary.

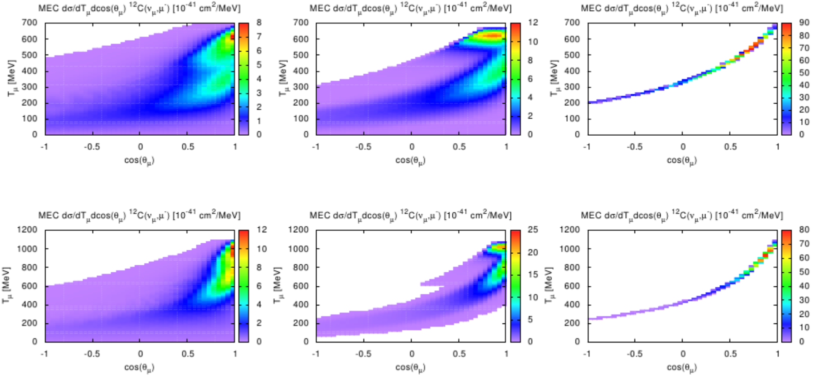
## NuWro

- the project started ∼ 2005 at the Wrocław University; an important encouragment from Danka Kiełczewska from Warsaw,
- main authors: C. Juszczak, J.Nowak, T. Golan, JTS
- the code is written in C++.
- can handle various target, fluxes
- to date, the only MC with MEC implementation,
- has a detector interface (used by Paweł Przewłocki in MEC studies)

## NuWro MEC models

- three models available: Nieves et al, Martini et al, and TEM (effective – vector part of MEC as enhancement of $G_M$),
- Nieves model implemented by J. Żmuda from cross section tables,
- hadron kinematics sampling algorithm by JTS (Phys. Rev. C86, 015504 (2012)) (always the same model)
    - two nucleons with $p_1$ and $p_2$ selected from the (L)FG momentum distribution.
    - $W^2 = (p_1 + p_2 + q)^2 > 4M^2$? Lorentz boost to CMS.
    - isotropic final nucleon sampling in CMS
    - boost back to LAB
- used by T2K in the MEC studies.

## NuWro MEC models – example:




from J. Żmuda

Top 800 MeV, bottom 1200 MeV. From left: Nieves, Martini and TE models.

# MEC – how two measure the effect?

The first idea: pairs of protons in the final state.

TABLE I. Predicted number of proton pairs with both momenta above various threshold values and two threshold values of the $\pi^\pm$ momentum. Simulations were done for 750-MeV muon neutrinos. The number of generated events is $2.5 \times 10^5$. The microscopic model in a NuWro implementation was used to produce signal events.

| $\pi^\pm$ cut [$\frac{MeV}{c}$]↓ | Proton cut [$\frac{MeV}{c}$] → | 300 | 400 | 500 |
|---|---|---|---|---|
| 0 | Signal | 7185 | 4201 | 1805 |
| | Background | 13 774 | 7928 | 2311 |
| 200 | Signal | 7231 | 4201 | 1805 |
| | Background | 16 158 | 8577 | 2388 |

TABLE II. The same as in TABLE I but for the NuWro implementation of the TEM.

| $\pi^\pm$ cut [$\frac{MeV}{c}$]↓ | Proton cut [$\frac{MeV}{c}$] → | 300 | 400 | 500 |
|---|---|---|---|---|
| 0 | Signal | 5457 | 2271 | 651 |
| | Background | 13 780 | 7961 | 2267 |
| 200 | Signal | 5465 | 2271 | 651 |
| | Background | 16 112 | 8691 | 2349 |

J.T.S., *Multinucleon ejection model for Meson Exchange Current neutrino interactions*, Phys. Rev. **C86** (2012) 015504.

# MEC – how two measure the effect?

An alternative is to look for integrated observables:

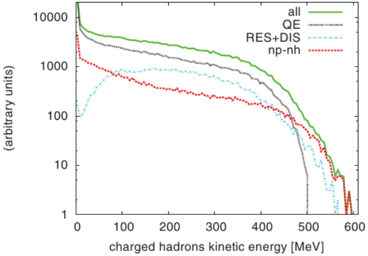



FIG. 12. (Color online) The distribution of hadronic kinetic energy for the events with cuts as described in the text. Simulations were done with 750-MeV muon neutrinos using NuWro implementation of the microscopic model. The number of generated events is $2.5 \times 10^5$. Contributions from CCQE, RES + DIS, and $np$-$nh$ events are also shown separately.

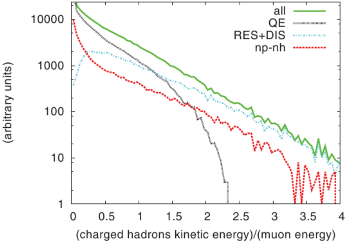



FIG. 14. (Color online) The distribution of hadronic kinetic energy normalized by the muon energy [see Eq. (7)] for the events with cuts as described in the text. Simulations were done with 750-MeV muon neutrinos using NuWro implementation of the microscopic model. The number of generated events is $2.5 \times 10^5$. Contributions from CCQE, RES + DIS, and $np$-$nh$ events are also shown separately.

J.T.S., *Multinucleon ejection model for Meson Exchange Current neutrino interactions*, Phys. Rev. C86 (2012) 015504.

## MINERvA CCQE measurement

Recently MINERvA published two papers with $\nu_\mu$ and $\bar{\nu}_\mu$ CCQE measurements.

- target is *CH*
- flux 1.5 to 10 GeV
- a first study that seriously investigates two body current contribution (not yet on the Monte Carlo level)

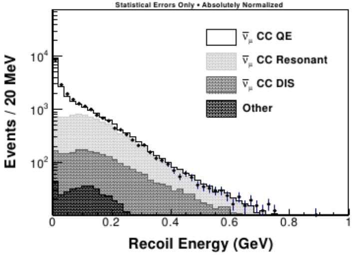
*Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV*, The MINERvA Collaboration, arXiv:1305.2234,

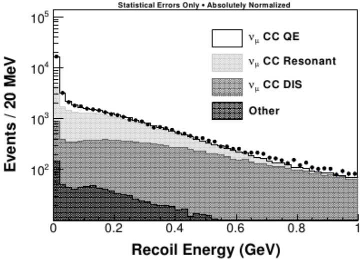
*Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV*, The MINERvA Collaboration, arXiv:1305.2243.

NuWro predictions are used extensively!

# MINERvA – selection of CCQE events

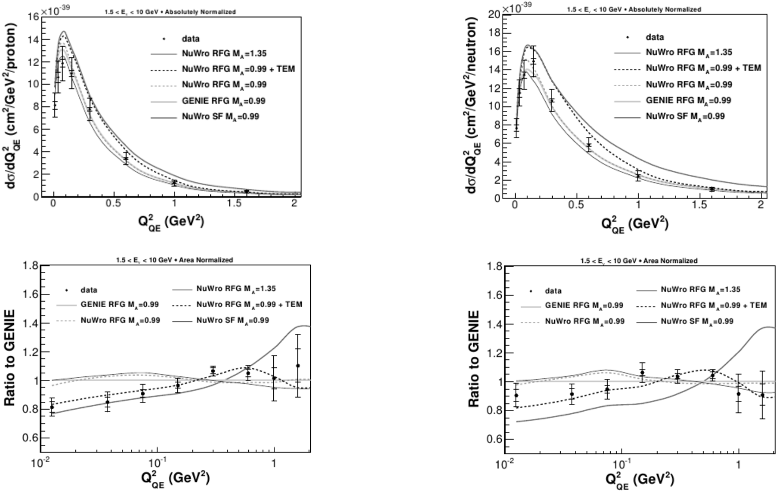
- $\mu^-$ or $\mu^+$ track
- a volume around interaction vertex divided in two parts
  - vertex energy region (for $\bar{\nu}_\mu$ containing proton (pion) tracks with 120 (65) MeV of kinetic energy; for $\nu_\mu$ containing proton (pion) tracks with 225 (100) MeV of kinetic energy)
  - recoil energy region used in event selection by making appropriate cuts (in $E_{recoil}$, $Q^2$ plane)



# MINERvA – results

A model with transverse enhancement MEC contribution provides the best agreement with the data (left $\bar{\nu}_\mu$, right $\nu_\mu$).



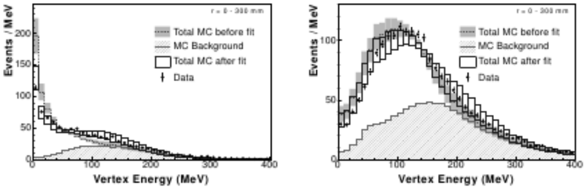
# MINERvA – vertex activity region.

Idea: data/MC comparison including tests with hypothetical extra protons.

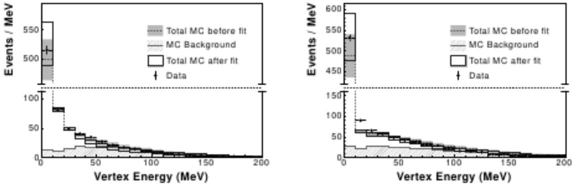
For $\nu_\mu$ the data prefer an addition of a final state proton with less than 225 MeV kinetic energy in $25 \pm 1(\text{stat}) \pm 9(\text{syst})\%$ of events.
For $\bar{\nu}_\mu$ the data prefer a removal of a final state proton in $10 \pm 1(\text{stat}) \pm 7(\text{syst})\%$ of events.

Left: $Q^2 < 0.2$ GeV$^2$, right $Q^2 > 0.2$ GeV$^2$.

$\nu_\mu$




$\bar{\nu}_\mu$



## Monte Carlo cascade models

Anambiguous identification of multinucleon knock-out events requires a reliable FSI model in MC.

- idea of Metropolis N. Metropolis et al., Phys. Rev. 110 (1958) 185 and 204
- semi-classical approach
- more sophisticated approach: GIBUU
- in medium pion-nucleon and nucleon-nucleon cross sections?
- needs nucleon knock-out data for validation.

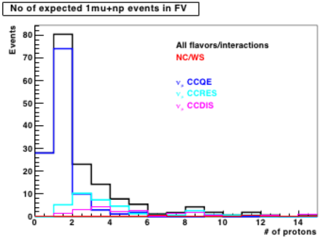
## ArgoNeuT proton multiplicity data.

A very low threshold for proton reconstruction: $T_p \simeq 22$ MeV.

### $\nu_\mu$ - neutrino mode run

| Multiplicity | Genie Expectation * | Genie % of Total | DATA** | DATA % of Total |
|---|---|---|---|---|
| 0p+1mu | 28±4 | 16% | 15±3 | 14% |
| 1p+1mu | 80±7 | 47% | 51±10 | 48% |
| 2p+1mu | 23±4 | 13.4% | 28±6 | 26% |
| 3p+1mu | 14±3 | 8.3% | 13±3 | 12% |
| 4p+1mu | 8±2 | 4.5% | 0 | 0 |
| TOTAL (including >4p) | 172±10 | - | 107±12 | - |

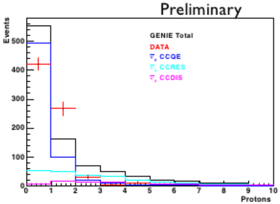
**Data 38% lower**

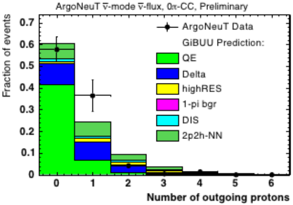



Kinga Partyka, NuInt12

# Proton multiplicity (1μ+Np)

| Multiplicity | Genie | Genie % of Total | DATA | DATA % of Total | Data/MC Ratio |
|---|---|---|---|---|---|
| 0p+1mu | 553±11 | 60% | 422±42 | 58% | 0.76 |
| 1p+1mu | 160±6 | 17% | 266±53 | 37% | 1.66 |
| 2p+1mu | 68±4 | 7% | 30±6 | 4% | 0.44 |
| 3p+1mu | 50±3 | 5% | 3±1 | 0.4% | 0.06 |
| 4p+1mu | 32±3 | 4% | 3±1 | 0.4% | 0.09 |
| TOTAL (including >4p) | 925±15 | - | 727±68 | - | 0.79 |




GiBUU (considered more reliable than MCs) has serious problems...

from: Tingjun Yang

## Conclusions and outlook

- a lot of theoretical and experimental activity in attempts to understand two body current contribution
- on theoretical side, a size of the contribution is very uncertain
- experimental searches are required
- investigation of vertex activity may be a key to success
- MC cascade models must be upgraded

Last but not least: What about T2K?...

# Thank you!