On measuring two body current contribution in neutrino-nucleus scattering

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INT Seattle

Outline:

- a very short introduction
- information contained in muon only
- pionless multinucleon knock out final states
  - pion absorption
  - CCQE followed by FSI
  - two body current events
- hadronic model for two body current events
  - a role of nucleon correlations
- possible observables
- quality of MC simulation tools
- summary

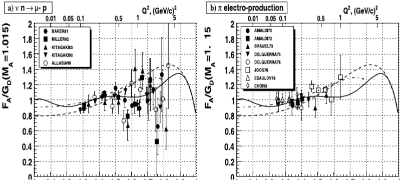
The problem: how large is two body current contribution to neutrino inclusive cross section?

- from electron scattering we know it is there
- theoretical estimates for neutrinos are uncertain and differ from each other (yesterday's Marco Martini talk)
- most likely it was seen in MiniBooNE (only muon observable) and MINERvA (hadronic observable: vertex activity) experiments

How large it is? Which is the best approach to measure it? Is that possible at all?!

Frustrating because it is about a large contribution to the neutrino inclusive cross section!

Large CCQE M_A controversy.

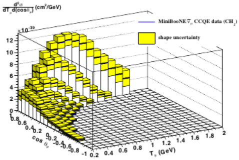


The experimental data is consistent with dipole axial FF and $M_A = 1.015$ GeV.

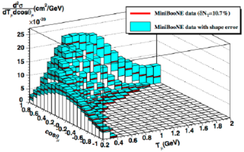
A. Bodek, S. Avvakumov, R. Bradford, H. Budd

- older M_A measurements indicate the value of about 1.05 GeV
- independent pion production arguments lead to the similar conclusion

MiniBooNE reported $M_A \sim 1.35$ GeV.



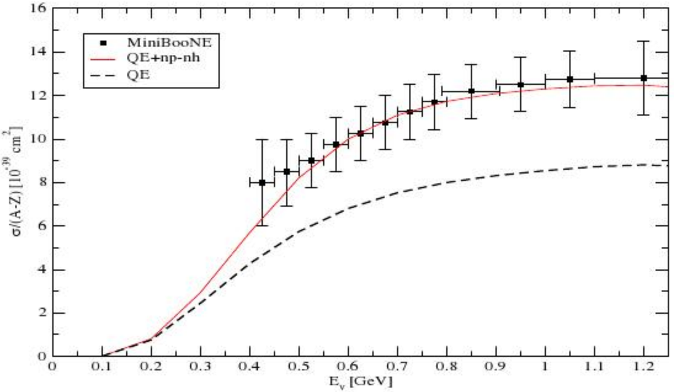
$\bar{\nu}_\mu$ CCQE



ν_μ CCQE

T. Katori, J. Grange

The solution of the MB large axial mass puzzle?



M. Martini, G. Chanfray, M. Ericson, J. Marteau

Theoretical models

All the theoretical models provide predictions for final state muon only:

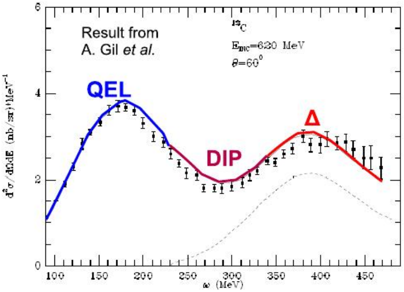
- Martini (Marteau) model; two options for elementary response functions
- IFIC (Nieves) model
- transverse enhancement model
- superscaling model
- effective GiBUU model/ansatz

Is this information sufficient to identify clearly and measure a strength of the two body current contribution?

In the case of electron scattering inclusive measurements there is a significant two body current contribution in the dip region. Perhaps it is sufficient to investigate muon final state only?

Two body current contribution from muon observable

In the electron scattering there is a problem of an access of the cross section in the DIP region between QE and Δ peaks:



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

- there is about 30 years long discussion on the *DIP* region
- the extra strength is believed to come from the two-body current dynamics

Typical two body current events: no pions in the final state.

In this talk in numerical analysis we impose a strict veto on final state pions. Such events origin from:

- CCQE with FSI effects,
  - exception is spectral function with short range correlation part: there are two nucleon knock-out events without FSI
- pion production and subsequent absorption
- two body current.

All the simulations are done in NuWro Monte Carlo event generator.

Predictions will be shown for 1 GeV muon neutrinos and also for MiniBooNE flux.

NuWro

- the project started $\sim$ 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 targets, fluxes, has a detector interface,
- open source project: http://borg.ift.uni.wroc.pl/nuwro/

NuWro is not an official MC in any experiment and serves as a laboratory for new developments.

New (or relatively new) ingredients:

- random phase approximation corrections on the top of Fermi gas model,
- two body current contributions,
- in medium modifications of NN cross sections (after Pandharipande, Pieper, PRC **45** (1992) 791)

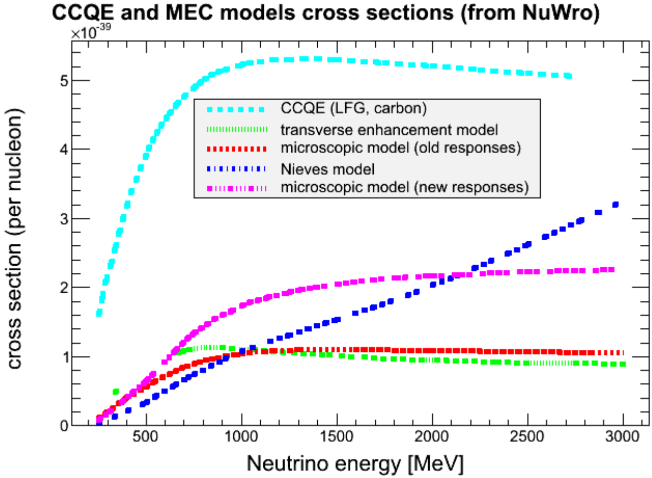
NuWro MEC models

Four options are available:

- Nieves et al model
  - implemented by J. Żmuda from cross section tables,
  - does not incorporate the latest upgrades of the model (work in progress)
- *microscopic* models (two)
  - similar to Marteau and Martini models,
  - $np - nh$ part expected to be very similar to Martini (Marteau) model
    - most of np-nh contribution not affected by RPA effects
  - based on: JTS, a talk at NuInt02, arXiv:nucl-th/0307047
  - two versions of elementary responses, old from the original Marteau model, new (almost) identical to those in the Martini model
- transverse enhancement model.

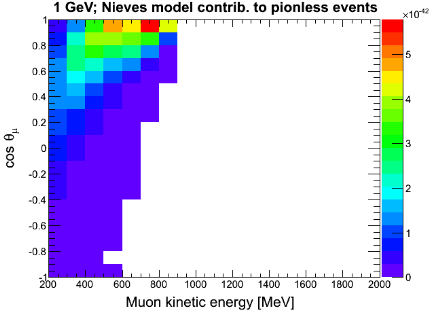
These are all models for a contribution to muon inclusive cross section. They provide no information about final state nucleons.

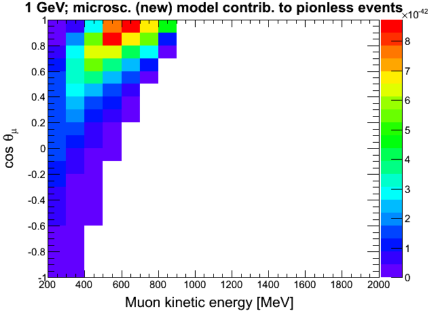
Models comparison – overall cross sections



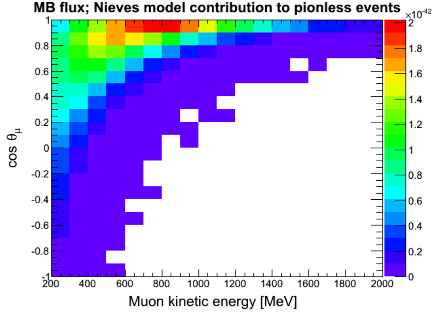
New microscopic cross section larger than Martini model.

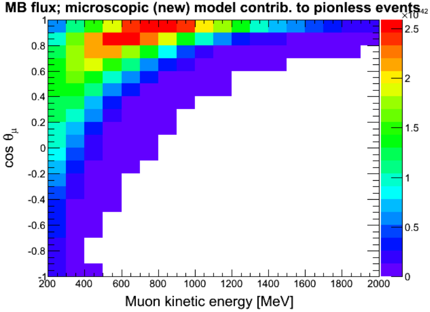
Models comparison – muon double differential cross sections





Models comparison – muon double differential cross sections

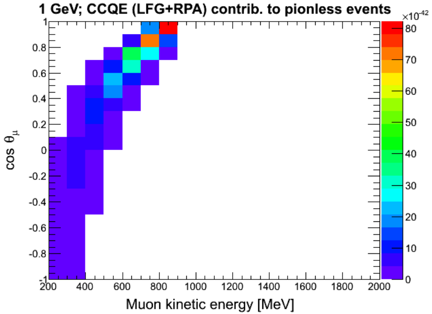


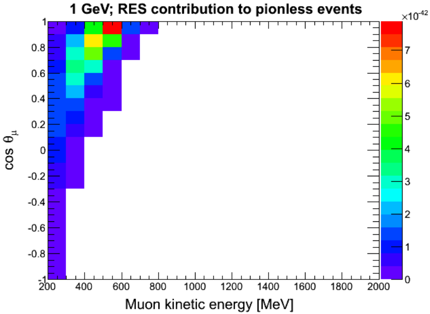


The model predictions are quite similar.
Nieves model covers larger phase space.

Two body current contribution from muon observable

In attempts to identify the signal we must consider pionless events resulting from CCQE and RES dynamical mechanisms:





Two body current contribution from muon observable

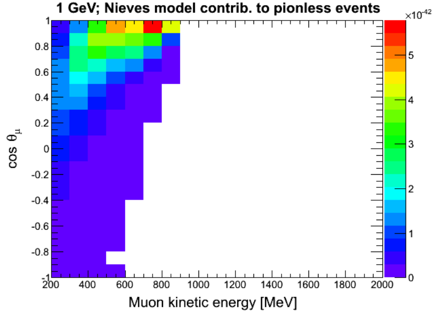
We will look for shape modifications in 2D differential cross section introduced by two body current events:

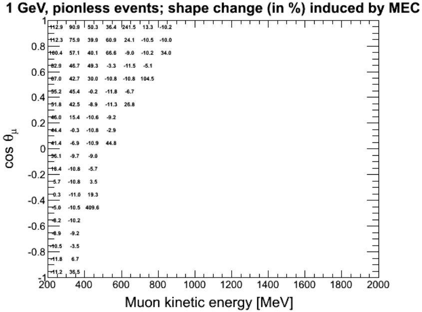
$$\frac{\frac{d^2\sigma^{with\ \ 2body}}{d\cos\theta_\mu dT_\mu} - \frac{d^2\sigma^{without\ \ 2body}}{d\cos\theta_\mu dT_\mu}}{\frac{d^2\sigma^{without\ \ 2body}}{d\cos\theta_\mu dT_\mu}}$$

with both $\sigma^{with\ \ 2body}$ and $\sigma^{without\ \ 2body}$ normalized to the same value.

Two body current contribution from muon observable

We analyze (on the right) how much **the shape** of double differential cross section is affected by inclusion of the two body current contribution.

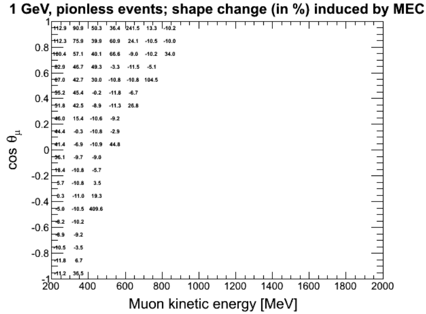


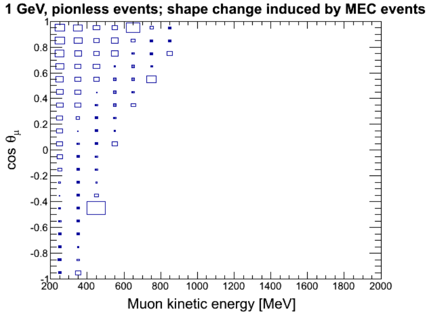


For monoenergetic neutrinos (1 GeV) there would be a clear and strong signal from the two body current in a region of high statistics! Analogy: dip region in electron inclusive scattering data.

Two body current contribution from muon observable

Another visualization:

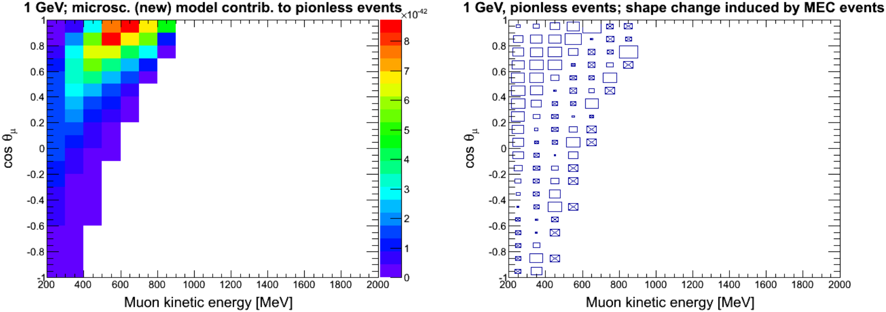




CCQE is modeled by LFG+RPA.

Two body current contribution from muon observable

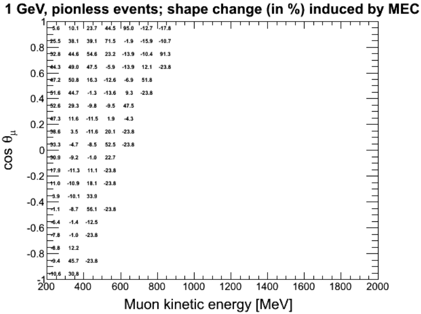
The pattern of modifications depends on details of the models used in numerical computations.
Another example: CCQE modeled by spectral function and MEC by (new) microscopic model.

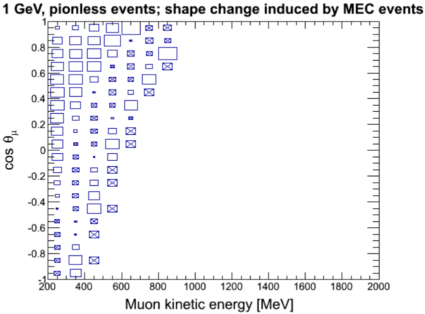


A strong signal (in the same bin) is always there.

Two body current contribution from muon observable

Another visualization:

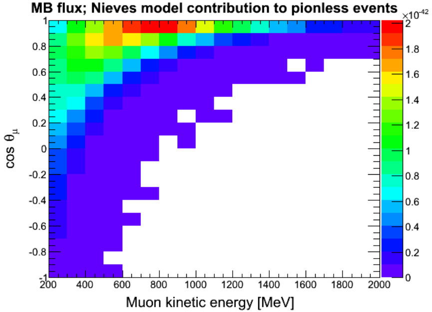


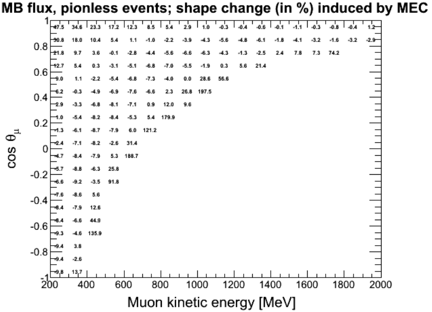


The CCQE model is spectral function.

Two body current contribution from muon observable

The impact of flux is devastating:

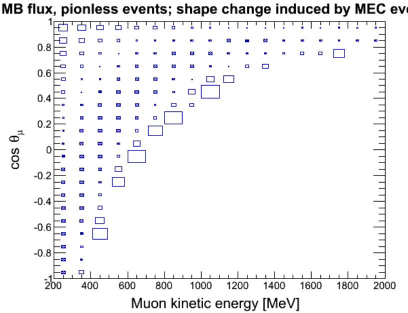


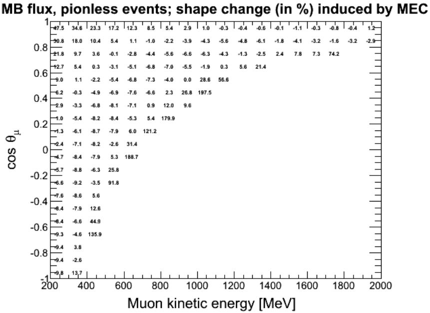


Significant shape modifications survive only in kinematical regions of low statistics. Measurement of the size of two body current contribution becomes difficult. There are big errors in MB 2D differential cross section data!

Two body current contribution from muon observable

Again, alternative visualization:





Two body current nucleon model

Perhaps there is more (or complementary) information in final state nucleons?

Nucleon model is badly needed.

The strategy:

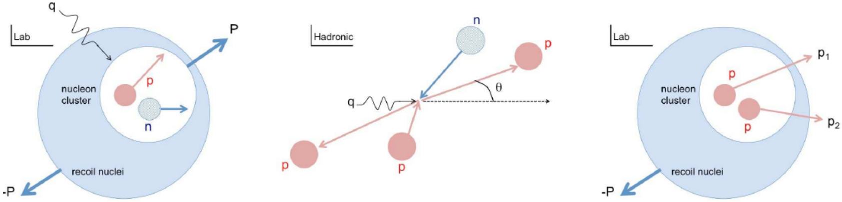
- start from a simple and flexible model
- identify possible observables
- identify most important assumptions
- look for observables robust wrt model assumptions

NuWro two body current nucleon model (JTS, Phys. Rev. C86, 015504 (2012))

Only muon information is used:

- muon's kinetic energy and production angle are known as an input
- equivalently, momentum and energy transfered to the hadronic system are known
- two/three nucleons are selected from the Fermi sea
- initial hadronic system is formed by adding all the four momenta
- boost to the hadronic center-of-mass frame (CMF) is performed
- in the hadronic CMF two/three nucleons are selected isotropically as a final state configuration
- boost back to the laboratory frame is performed
- Pauli blocking may be checked
- energy balance must be consistent with the FSI (in NuWro Fermi energy and 7 MeV as a potential well is subtracted at the end of the cascade)
- events are weighted by muon double differential cross section.

NuWro two body current nucleon model (JTS, Phys. Rev. C86, 015504 (2012))

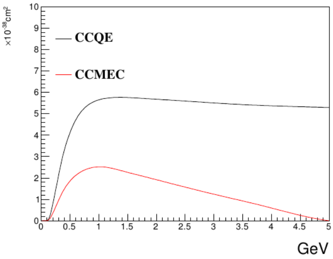


T. Katori

Strictly speaking the above figure describes GENIE nucleon model (see later) – but both are virtually identical.

The same hadronic model will be combined with four theoretical models for two body current contribution to muon inclusive cross section.

Other MC (MC like) approaches



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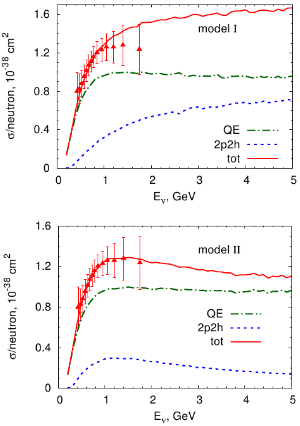
GENIE model

- Dytman ideas for strength (based on the Lightbody bodel): Gaussian distribution between QE and Δ peaks
- *nucleon cluster model* for nucleons, very similar to NuWro approach

Other MC (MC like) approaches



GIBUU

- simple ansatz for matrix element: either a constant (model I) or transverse projection (model II), in both cases strength adjusted to the MiniBooNE data

Other MC (MC like) approaches

TABLE 1. Comparison of MEC models in neutrino interaction generators.

	GENIE	NuWro	GiBUU
Leptonic model	Dytman model	TEM, np-nh model, and Valencia model	Transverse projector
Hadronic model	nucleon cluster	nucleon cluster	phase space density
initial nucleon momentum	Fermi sea	Fermi sea	Fermi sea
initial nucleon momentum correlation	none	none	none
initial nucleon spatial correlation	none	none	2 nucleons are generated at the same location
initial nucleon pair	n-p:n-n=1:4 isospin ansatz	n-p:n-n=9:1 short range correlation	n-p:n-n=12:5 statistical average
FSI model	hA model	cascade model	BUU transport

T. Katori, *Meson Exchange Current (MEC) Models in Neutrino Interaction Generators*, arXiv:1304.6014 [nucl-th].

NuWro two body current nucleon model – flexibility

Isospin correlations:

- how many n-p and n-n in pairs participate in interactions ?
- no obvious theoretical argument
- a fraction of n-p pairs is a free parameter
- default value is 0.7; later some comparisons with 0.9 will be shown

Momentum correlations:

- momenta of nucleon pairs participating in interaction ?
- default option (following Marteau/Martini and Nieves models): momenta are selected at random from Fermi see
- alternative: back-to-back momenta with a distribution given by spectral function – some comparisons will be shown later

Observables.

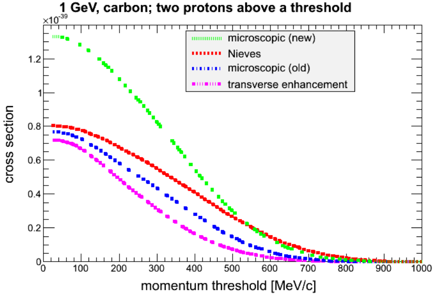
We are looking for pionless final states.

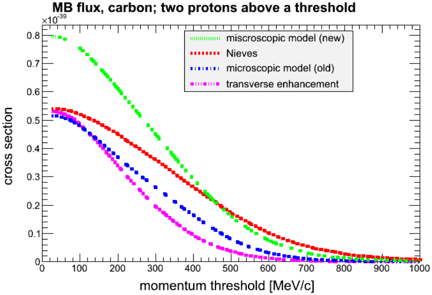
As said before, the background comes from:

- CCQE followed by FSI
- pion production and absorption

Two (at least) protons in the final state

The models predictions are quite different:



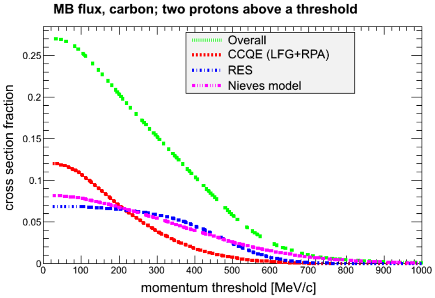


Predictions depend mostly on

- overall cross sections
- differential cross section in energy transfer.

Two protons in the final state

Now, include also background, i.e. similar events coming from CCQE and RES interactions.
Normalization is relative wrt overall cross section.

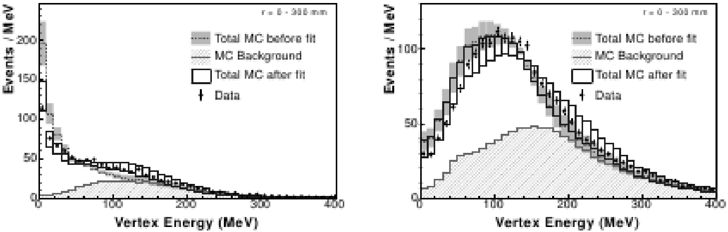


For realistic p_{thr} (in T2K $\sim$ 500 MeV/c) the problem is background coming from pion absorption.

Reconstructed protons and vertex activity

Some information is there in vertex activity – energy deposited near interaction vertex, not identified as a proton track.

- succesfully explored by MINERvA!

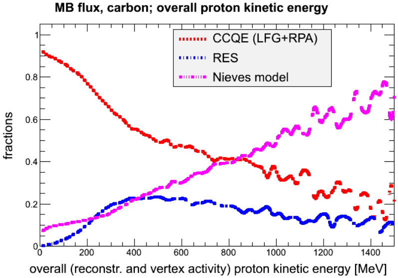


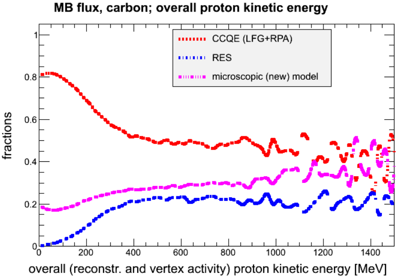
Fiorentini et al [MINERvA Collaboration], PRL 111 (2013) 022502.

Below we assume that there are no pions and neutrons are not visible at all. It means, that vertex activity energy comes from low momentum protons only. It is difficult to make better without detector simulations.

Reconstructed protons and vertex activity

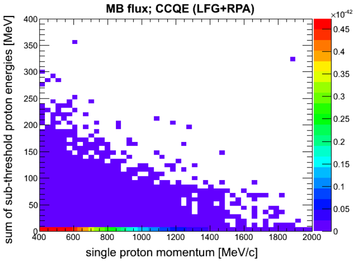
The simplest observable is a sum of kinetic energies of all reconstructed protons and vertex activity

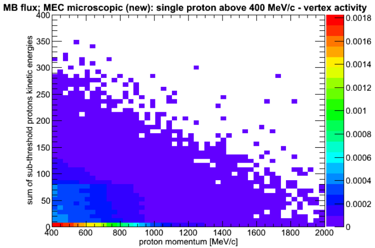


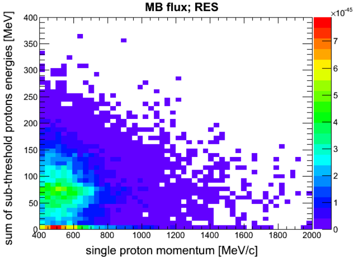


For Nieves model the shape of distribution is modified in a unique way due to the presence of two body current contribution. However, this prediction is model dependent.

Single reconstructed protons and vertex activity assuming 400 MeV/c reconstruction threshold.

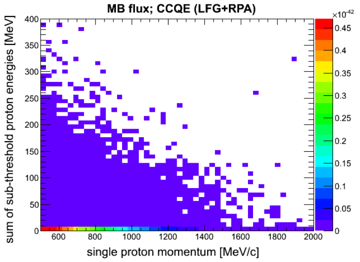


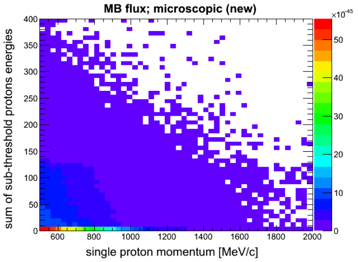


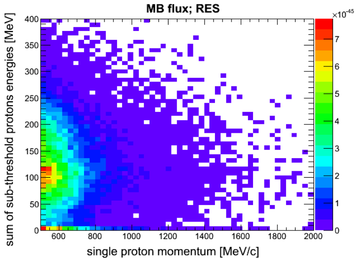


- there is always a large contribution from events without FSI effects
- a structure seen in RES is in low cross section region

Single reconstructed protons and vertex activity assuming 500 MeV/c reconstruction threshold.

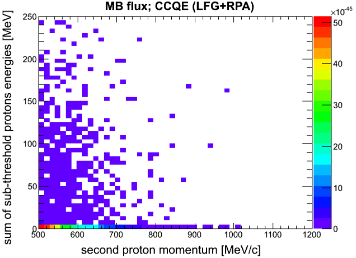


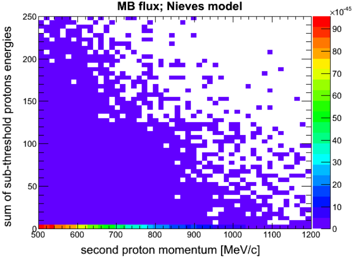


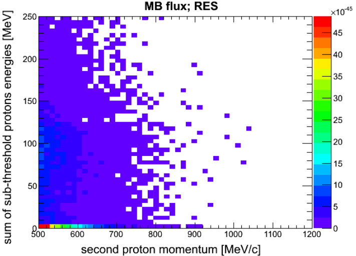


- amount of vertex activity is increased

Two reconstructed protons and vertex activity assuming 500 MeV/c reconstruction threshold







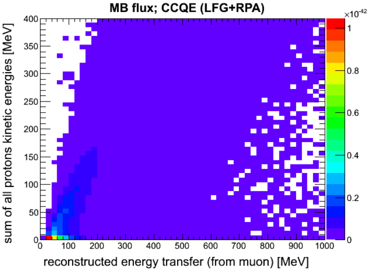
- events with no vertex activity – no FSI took place
- there is nothing characteristic for two body current events

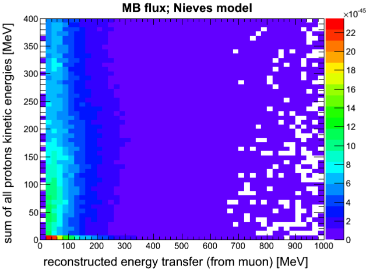
Muon and proton information put together

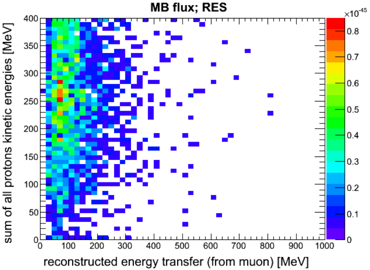
Finally, one can combine information from muon, reconstructed protons and vertex activity.

Using muon 3-momentum one can *reconstruct* its energy (CCQE assumption) and then also energy transfer. This can be compared with overall visible proton energy:

Muon and proton information put together



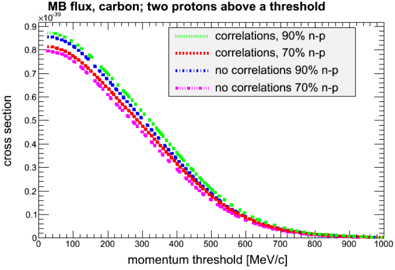


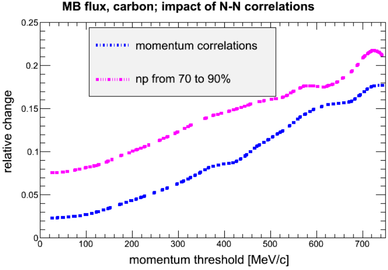


- there is a kinematical region where two body current may dominate
- seems to be a promising observable, but the cross section may be too low.

Correlation effects

Impact of correlation effects on number of proton pairs in the final state:





Isospin and momentum correlations are analyzed seperately. A possible confusion: In above figures correlations means initial state nucleon momenta are back-to-back.

Results for (new) microscopic model.

Monte Carlo generators validation

Important question, avoided so far: how reliable are NuWro Monte Carlo simulations?

In the past MC FSI studies focused on pion cascade mainly. Performance of nucleon cascade models was not studied that much.

In what follows: some NuWro validation studies.

NuWro validation – pion absorption final states (LADS data)

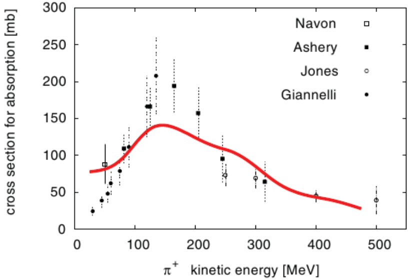
charge multiplicity (in %)	1C	2C	3C	$\geq$ 4C
argon 118 MeV (LADS)	34.3	56.6	8.8	0.3
argon 118 MeV (NuWro)	36.6	54.7	8.2	0.5
argon 239 MeV (LADS)	18.2	53.8	24	3.9
argon 239 MeV (NuWro)	25.5	50	20.5	4
nitrogen 118 MeV (LADS)	22.8	63.3	13.2	0.8
nitrogen 118 MeV (NuWro)	25.2	63.3	10.6	0.9
nitrogen 239 MeV (LADS)	10.2	53.4	29.9	6.5
nitrogen 239 MeV (NuWro)	16.9	52.6	25.2	5.3

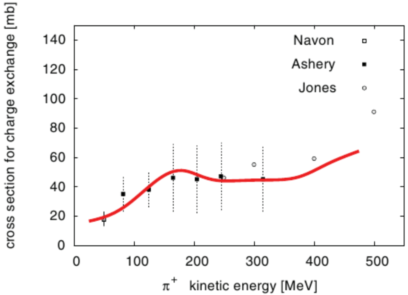
LADS data from Rowntree et al, PRC60 (1999) 054610

- LADS seperates protons and deuterons; in NuWro only protons
- in NuWro momentum cut 200 MeV/c is imposed. Energy threshold for proton detection in LADS is $16-22$ MeV i.e. $175-200$ MeV/c.

LADS: *[limitations of the detector] most commonly cause high final state multplicities to be understated and also lower multiplicities to be overstated [...] Rudimentary estimates indicate that in severe cases (e.g. a three nucleon final state at 118 MeV) roughly 70% of actual strength is observed.*

NuWro validation – pion absorption and charge exchange rate





NuWro validation (cont)

ArgoNeut LAr proton multiplicity data. Reconstruction threshold is 21 MeV of kinetic energy ($\sim$ 204 MeV/c).

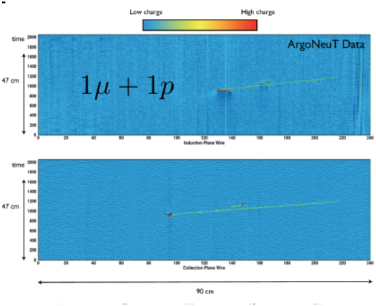
TABLE 1. Data comparison with GENIE for proton multiplicity of μ+Np events for neutrinos in neutrino mode with statistical and preliminary systematic uncertainties.

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

TABLE 2. Same as Table 1 for antineutrinos in anti-neutrino mode.

Multiplicity	Genie Expectation	Genie % of Total	DATA	DATA % of Total
0p+μ	553±11	60%	422±42	58%
1p+μ	160±6	17%	266±53	37%
2p+μ	68±4	7%	30±6	4%
3p+μ	50±3	5%	3±1	0.4%
4p+μ	32±3	4%	3±1	0.4%
Total(including>4p)	925±15	-%	727±68	-%

K. Partyka (ArgoNeut)



K. Partyka (ArgoNeut)

ArgoNeut proton multiplicity data – neutrino flux

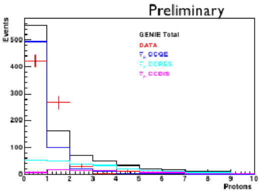
# protons (%)	data	NuWro	GENIE
0	14	15.4	16.3
1	48	50.8	46.5
2	26	17.8	13.4
3	12	9.6	8.1
≥ 4	0	6.3	15.7

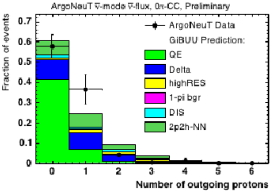
- experimental errors are of the order of 20%,
- GENIE predicts too many protons in the final state; NuWro had similar problems – Pandharipande, Pieper modifications are important.

ArgoNeut proton multiplicity data – antineutrino flux

# protons (%)	data	NuWro	GENIE
0	58	64.9	59.8
1	36.6	22.7	17.3
2	4.1	8.0	7.3
3	0.4	2.8	5.4
≥ 4	0.4	1.6	10.2

Below also GIBUU results (seem to be similar to NuWro)

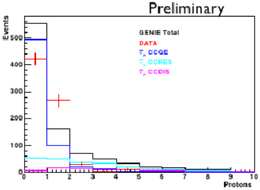


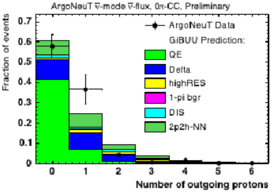


ArgoNeut proton multiplicity data – antineutrino flux

# protons (%)	data	NuWro	GENIE
0	58	64.9	59.8
1	36.6	22.7	17.3
2	4.1	8.0	7.3
3	0.4	2.8	5.4
≥ 4	0.4	1.6	10.2

Below also GIBUU results (seem to be similar to NuWro)





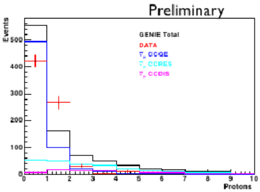
Tingjun Yang

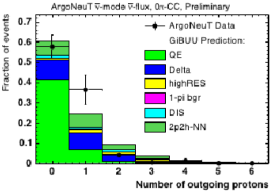
Yesterday Ornella told me that the data should be modified!

ArgoNeut proton multiplicity data – antineutrino flux

# protons (%)	data	NuWro	GENIE
0	67.7	64.9	59.8
1	23.7	22.7	17.3
2	6.4	8.0	7.3
3	1.4	2.8	5.4
≥ 4	1.0	1.6	10.2

Below also GIBUU results (seem to be similar to NuWro)





Tingjun Yang

With the new data agreement is even better

Summary:

- in order to measure two body current contribution final state nucleons should be investigated
- it is necessary to seperate background from pion absorption and FSI effects
- reliable MC simulation tools are required
- a role of nucleon-nucleon correlations should be understood
- experimental searches combined with further MC studies must be done.

Thank you!

Back-up slides

Nuclear correlations

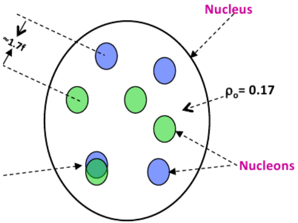
Fermi gas model completely neglects nucleon-nucleon correlations.

From electron scattering experiments we know that $\sim 20\%$ of time nucleons are strongly correlated in pairs with large $\sim$ back to back momenta.

- for $|\vec{p}| \leq\sim 600$ MeV/c corrections are expected to be due to tensorial nuclear force and pairs to be deuteron like with isospin $I = 0$ (proton-neutron only).

A typical distance between nucleon is 1.7 fm

A correlated pair:



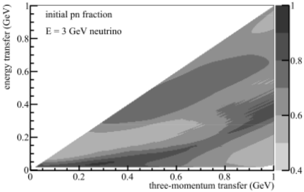
A. Bodek

Three nucleon correlations are very unlikely (0.5%).

Two body current neutrino computations

- inclusion of the two body current contribution leads to good agreement with the MB CCQE data with $M_A \sim 1.05$ GeV.
- neutrino energy unfolding procedures should be accordingly modified
- difficult to get predictions for final state nucleon momenta (JTS, PRC86, 015504 (2012)), important ArgoNeut data discussed in Dave's talk

Microscopic model prediction for isospin of the initial state nucleons:



R. Gran, J. Nieves, F. Sanchez, M.J. Vicente-Vacas

The average fraction of p-n pairs is 67%.

Microscopic models can be extended to energies up to 10 GeV (R. Gran, J. Nieves, F. Sanchez, M.J. Vicente-Vacas, arXiv:1307.8105 [hep-ph])

- important role of correlations introduced within the random phase approximation (RPA) approach and 2p-2h contribution
- RPA brings in a strong suppression at $Q^2 \sim 0$ (a factor of 0.6) and some enhancement for $Q^2 \geq 0.4$ GeV^2.

Beyond Fermi gas ground state computations

- results from J. Carlson, J. Jourdan, R. Schiavilla, I. Sick, Phys. Rev. C**65** (2002) 024002 for electron scattering suggest that it is very important to consider a realistic ground state
- non-relativistic computations done for light nuclei: ^{3}H, ^{4}H and ^{6}Li in the language of Euclidean responses and sum rules
  - almost all the enhancement of the strength due to two-body current comes from proton-neutron, and not from proton-proton or neutron-neutron pairs
  - when ground state correlations are neglected (Fermi gas model) the extra strength due to two-body current contributions becomes very small.