Multinucleon ejection – how to measure the effect?

Jan T. Sobczyk

FermiLab
(on sabbatical from the Wrocław University)

February 27, 2012

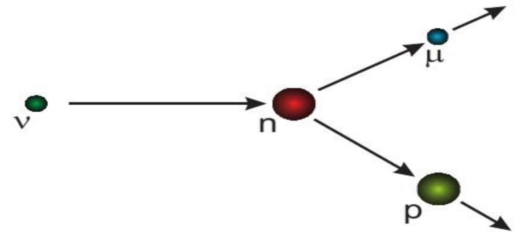
Outline

- CCQE large axial mass problem
- multinucleon ejection hypothesis
- *sources* of multinucleon final states
- microscopic models – an overview
- a simplified Marteau model
- generation of final nucleon states
- Monte Carlo implementation
- how to measure the new effect?

Quasielastic reaction on a free nucleon target

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

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



Everything is clear. Muon and proton in the final state.

Energy and momentum transfer differences of energy (momentum) between initial and final lepton.

Basic theory

$$\mathcal{H}_{int} = \frac{G}{\sqrt{2}} \left(\bar{\mu}\gamma_\alpha(1-\gamma_5)\nu_\mu\right) J^\alpha + h.c.$$

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

$$\Gamma^\alpha = \gamma^\alpha F_V(Q^2) + i\sigma^{\alpha\beta} q_\beta \frac{F_M(Q^2)}{2M} + \gamma^\alpha\gamma_5 F_A(Q^2) + q^\alpha \gamma_5 F_P(Q^2),$$

where

$$q^\mu \equiv p'^\mu - p^\mu, \qquad Q^2 \equiv -q_\mu q^\mu$$

CVC

Vector part of the current is known!

$$F_V(Q^2) = F_1^{(p)}(Q^2) - F_1^{(n)}(Q^2)$$
$$F_M(Q^2) = F_2^{(p)}(Q^2) - F_2^{(n)}(Q^2),$$

where

$$_{p,n} < p'|J^\alpha_{em}|p >_{p,n} = \bar{u}(p')\Gamma^\alpha_V u(p)$$

$$\Gamma^\alpha_V = \gamma^\alpha F_1^{p,n}(Q^2) + i\sigma^{\alpha\beta} q_\beta \frac{F_2^{p,n}(Q^2)}{2M}.$$

Electromagnetic FF is a well understood input to neutrino cross section predictions.

Partially conserved axial current (PCAC) hypothesis:

$$F_P(Q^2) = \frac{2M^2 F_A(Q^2)}{m_\pi^2 + Q^2}.$$

β-decay

$$F_A(0) \equiv G_A \approx 1.26.$$

Dipole axial FF hypothesis (the option discussed in this talk)

$$F_A(Q^2) = \frac{G_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}.$$

Axial mass

In the basic theory of CCQE assuming the dipole axial form factor...

- the only unknown quantity is M_A, axial mass,
- its precise value must be determined experimentally,
- M_A determines both the overall integrated cross section and the shape of $\frac{d\sigma}{dQ^2}$,
- because of large flux uncertainty the shape analysis is a preferable way to get the value of M_A.

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 pions give rise to 3 subevents

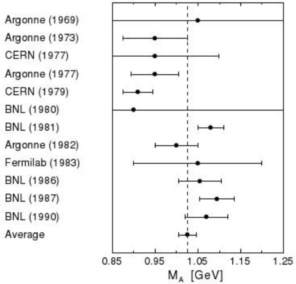
QE reaction on nuclear target - NOMAD

- 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?!...

CCQE axial mass puzzle

Until few years ago it seemed that the measurements converge to a value of the order $M_A \sim 1.03$ GeV.
There is a disagreement between old, mainly deuterium (left), and recent (right) M_A measurements.

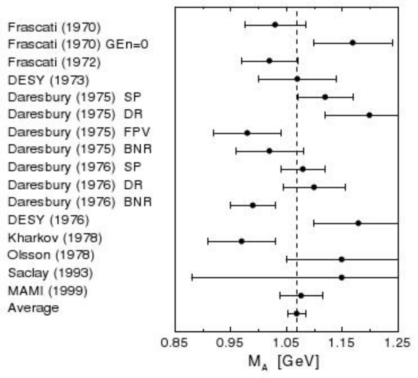


[from Bernard, Elouadrhiri, Meissner]

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

Axial mass - pion electroproduction argument

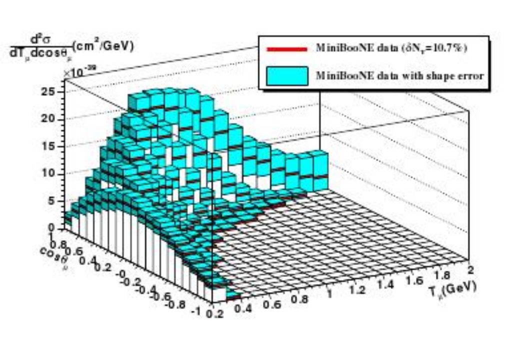
An independent theoretical argument in favour of a low value of M_A coming from PCAC.



The transition amplitude is written in multipole expansion. At the threshold two amplitudes contribute; E_{0+} and L_{0+}. Nambu, Lurie and Shrauner proved the low energy theorem: electric dipole amplitude $E_{0+}^{(-)}$ at the threshold can be expressed in terms of $G_A(Q^2)$.

MiniBooNE double differential cross section data

The data is available in the form of double differential cross section in muon kinetic energy and production angle:



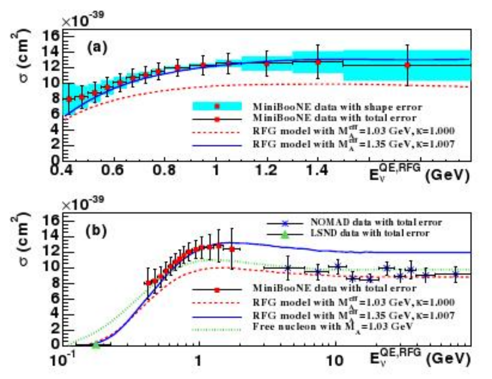
A.A. Aguilar-Arevalo et al.,[MiniBooNE collaboration] Phys. Rev. D81, 092005 (2010)

The best fit value is $M_A^{eff} = 1.35 \pm 0.17$ GeV, $\kappa = 1.007 \pm 0.012$ (see later).

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

MiniBooNE CCQE cross section data

Hypothesis: a large value of M_A^{eff} accounts for other dynamical mechanisms which contribute to the MB's CCQE sample.



If the value of M_A is raised from 1.03 to 1.37, the total CCQE cross section is increased by $\sim 30\%$, the huge effect!

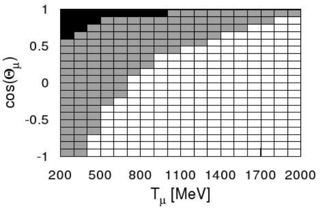
J-S-Ż

Possible explanantion: a poor nucleus model in NUANCE?

- both Spectral Function and Fermi Gas model
- fitting both M_A and the overall normalization λ
- fitting to the 2D differential cross section

Low momentum transfer cut

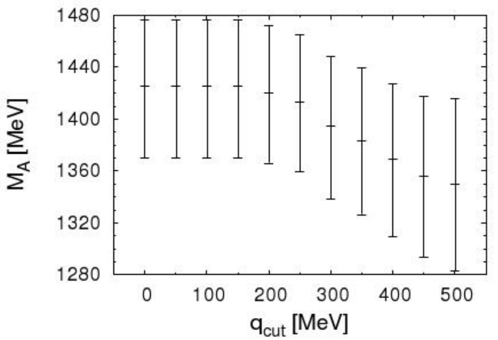
Bins with large (over 50%) contribution from the momentum transfer below q_{cut} (in black) are excluded from the analysis:



- $q_{cut} = 400$ MeV/c
- the excluded region contains almost all the bins for which Butkevich reported disagreement with the data!

J-S-Ż; low momentum transfer cut

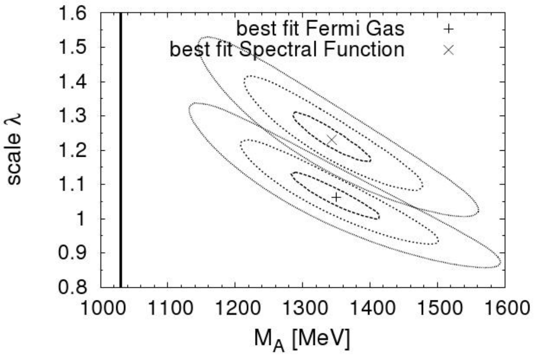
An impact on the best fit value of M_A:



For still larger q_{cut} statistical fluctuations appear (one looses more and more information).

The best fit value of M_A becomes smaller but the effect is not strong enough.

J-S-Ż; final results



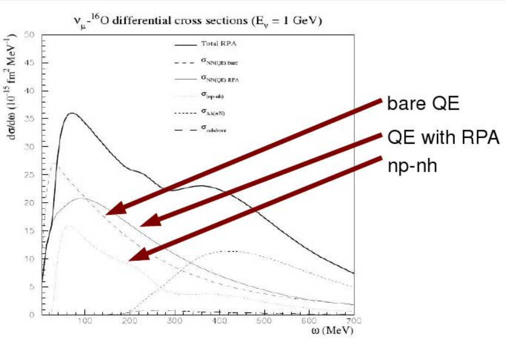
$q_{cut} = 500$ MeV/c. 1-, 3- and 5σ regions are shown above.

- fits for M_A are very similar for FG and SF
- difference in cross section values for FG and SF is compensated by λ
- $M_A = 1.03$ GeV is excluded on the beyond 5σ level

Results are consistent with MB but 1σ region is smaller.

Marteau model

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



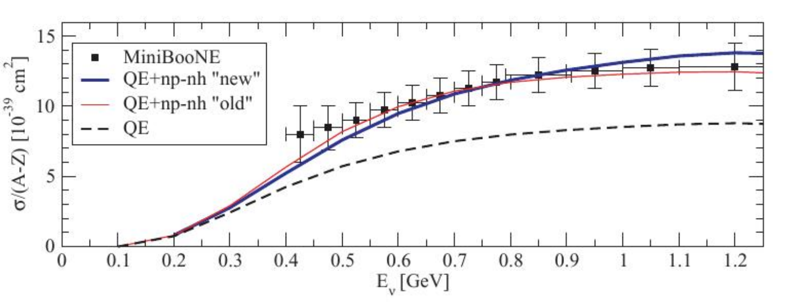
The original idea was put forward by Magda Ericson in 1990: appearance of pion branch, a collective state which decays into a pair of nucleons.

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.

How large?
$\sim$ a half of *bare QE* part!

Martini et al computations

Martini et al continued the work on the Marteau model obtaining ...



Does it mean that the problem is solved?...

Initial state correlations

- In the SF there is a contribution from initial state correlations (SRC - Short Range Correlations) leading to high momentum pairs of nucleons (mainly p-n)
- computations done in the Impulse Approximation lead to two-nucleon ejection (one nucleon is a spectator).

Final State Interactions

- there can be multinucleon final states from standard QE primary interaction
- there can be multinucleon final state coming from pion absorption
- FSI effects change nucleon momenta and can increase number of ejected nucleons.

Microscopic computations

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

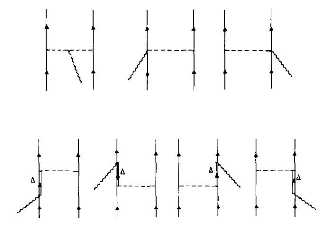
There are also effective models:

- Bodek, et al
- Steve Dytman model in GENIE

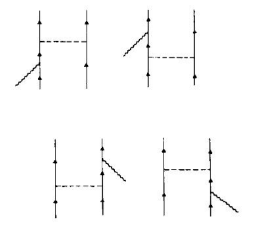
Typically, the models provide muon inclusive 2D cross section and a seperate problem is to get predictions for final state nucleons.

Diagrams and vocabulary

We distiguish the following elementary diagrams which can lead to two-nucleon emission:



top: pion-in-flight, contact diagrams; bottom: Δ diagrams

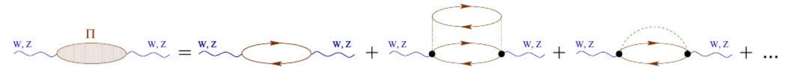


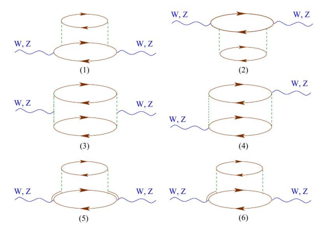
correlation diagrams

from Alberico, Ericson, and Molinari, Ann. Phys. 1984

Diagrams and vocabulary

A possible source of confussion: sometimes diagrams are presented in a different fashion as contributions to virtual W/Z boson self-energy with Cutkosky cut rules:





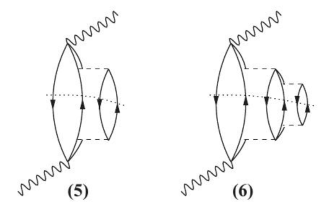
from Luis Alverez-Ruso, NuInt11

Models – which diagrams are there

- MEChM -> Δ and correlation diagrams (no pion-in-flight and contact)
- Nieves et al -> all
- Amaro et al -> pion-in-flight, contact and Δ diagrams (no correlation) (in the electron scattering paper they include all the contributions)

Remark: the Δ in-medium decay contribution

There is one contribution which is rather easy to implement in MC's:



A suitable parameterization of the Δ width in the nucleat matter exists (Oset, Salcedo). Extra contributions lead to two- and three-nucleon ejection.

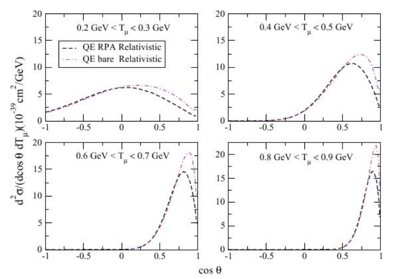
It should not be confused with real pion absorption!

Relativistic/non-relativistic

- Nieves and Amaro models are relativistic
- MEChM model is basically non-relativistic, but several standard relativistic corrections were added (it is shown that they are quite important and lead to a redistribution of strength)

RPA and other ingredients

- all three models are based on the Fermi Gas
- MEChM and Nieves models have RPA corrections (π and ρ mesons, contact Landau-Migdal terms)
- for an agreement with the MB data RPA effects are quite important (below MEChM model):



RPA effects are seen in the forward direction.

A scaling; isospin

MEChM model predicts that for medium size nuclei like calcium np-nh contribution *per nucleon* is more or less the same as for carbon.
Authors of MEChM paper argue that for CC neutrino reaction there are much more p-p than p-n pairs. Two interesting statements:

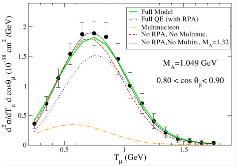
1) *This predominance has the same origin as for p-wave* π^- *absorption by nuclei where n-n emission is favored over n-p emission.*

2) *The spin-dependent part of the neutrino interaction with n-p pair is stronger than with the same two nucleons when isolated.*

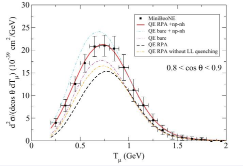
MiniBooNE data

- MEChM and Nieves report agreement with the MB data
- Amaro et al underestimate the cross section (however, there are several simplifications in the other ingredients of the model)

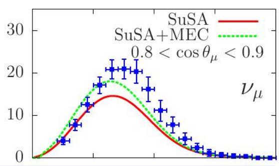
Direct comparison is possible in one kinematical region for which all three groups show their results:



Nieves et al

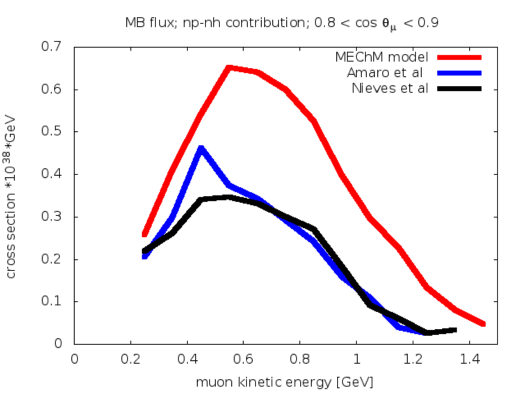


MEChM



Amaro et al

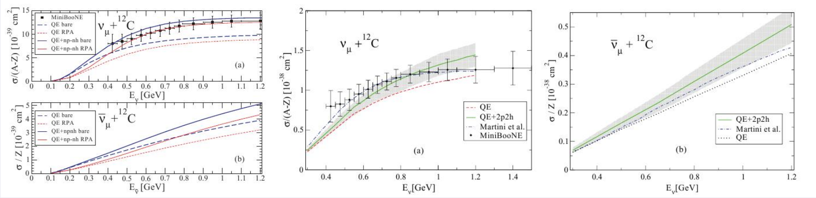
MiniBooNE data



Remember that there is no correlation contribution in the Amaro et al computations!

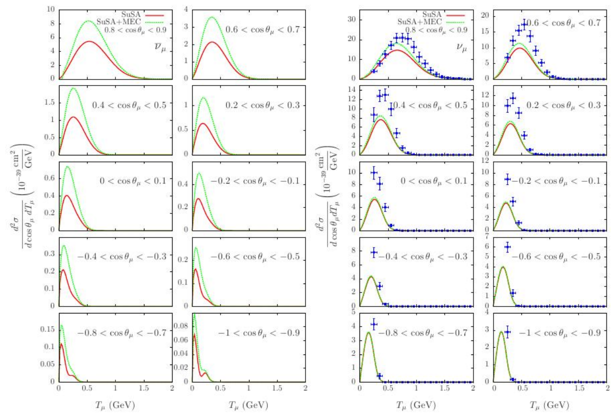
Neutrinos/antineutrinos

- MEChM predicts smaller effect for antineutrinos (argument: np-nh is dominated by the transverse response and for antineutrinos two transverse contributions enter with opposite signs).
- Nieves et al model predicts large np-nh contribution both for neutrinos and antineutrinos
- Amaro et al model predicts larger effect for antineutrinos



MEChM Nieves et al

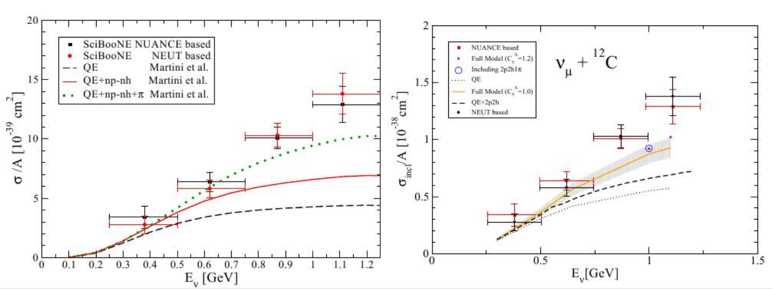
Neutrinos/antineutrinos



Amaro et al

Inclusive CC

Nieves et al and MEChM allow for a comparison with SciBooNE inclusive CC cross section data:

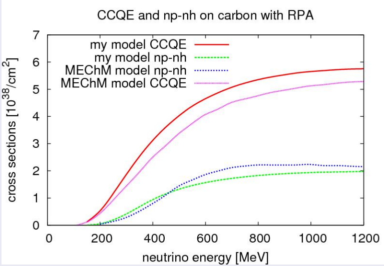


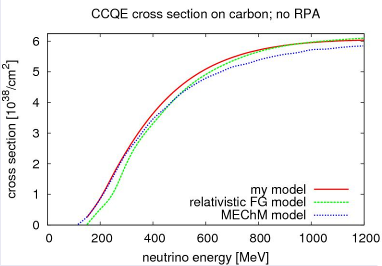
On the left MEChM and on the right Nieves et al model.

The simplified Marteau model

- departure point: an old investigations of the Marteau model presented at NuInt02 [J.T.S, *Modeling nuclear effects in neutrino interactions in 1-GeV region*, nucl-th/0307047]
- desclaimer: it is not the MEChM model
- no Local Density Approximation
- but includes RPA, Δ width (pionless decays), elementary 2p-2h excitations
- reproduces (hopefully) basic features of the MEChM model
- the model is more *relativistic*: it is based on the **relativistic** Fermi Gas model unlike MEChM

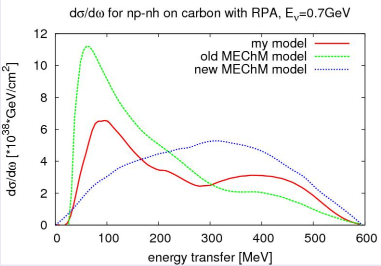
The model – comparison with MEChM (1)

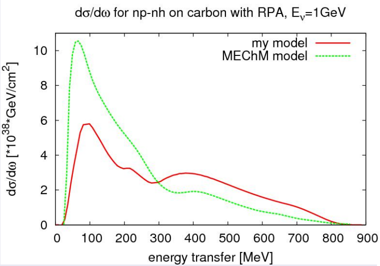




My CCQE with RPA is smaller than MEChM. But it is closer to relativistic FG! My np-nh contribution is smaller, at 700 MeV by 20-25%.

SM model – comparison with MEChM (2)





I show predictions from two versions of the MEChM model.
WARNING: the shapes are different – this impacts the predictions.

The model of nucleon ejection

The basic idea: as it is very difficult to get predictions from the sophisticated models, use only muon information!

- one knows muon's kinetic energy and production angle...
- equivalently, one knows momentum and energy transfer...
- one selects 2(3) nucleons from the Fermi see...
- one adds the energy and momentum being transfered...
- one boosts to the CMF of the hadronic system...
- in the CMF one selects isotropically 2(3) nucleons in the final state...
- one boosts back to the LAB frame.

The model of nucleon ejection

- All the correlations are disregarded
  - remark: deuteron-like initial state leads to very similar results; the most important assumption is in the CMF boost trick!
  - interestingly, some correlations are implicit: many configurations are kinematically forbidden
- there are no good arguments how many pairs are n-n and n-p – combinatorics?!...
- what we calculate should not be confused with scattering on strongly correlated pairs (Short Range Correlations), where an interaction occurs on only one nucleon and not on a pair.

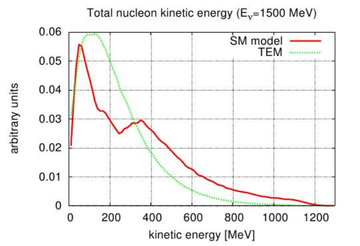
The model of nucleon ejection

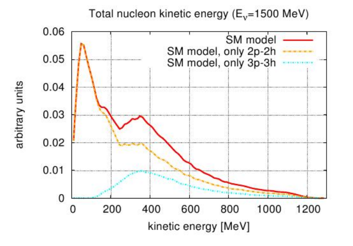
There are many options to impose an energy conservation

- assume nucleons to be in the potential well $E_{Fermi} + 8$ MeV
- subtract from each nucleon E_{Fermi} from the very beginning (nucleons are put off shell)
- FSI effects (e.g. using NuWro cascade model)
- subtract 8 MeV at the end, adjusting nucleon momentum (on shell)
- it can happen that a nucleon cannot leave nucleus, but the event is assumed to have occured
- another option: impose Pauli blocking and subtract $E_{Fermi} + 8$ MeV at the end

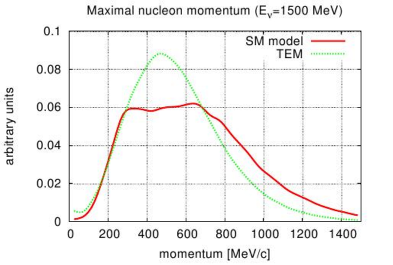
Some predictions (1)

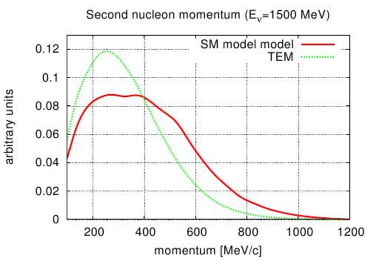
Typical predictions from simplified Marteau (SM) and Transverse Enhancement Model (TEM).





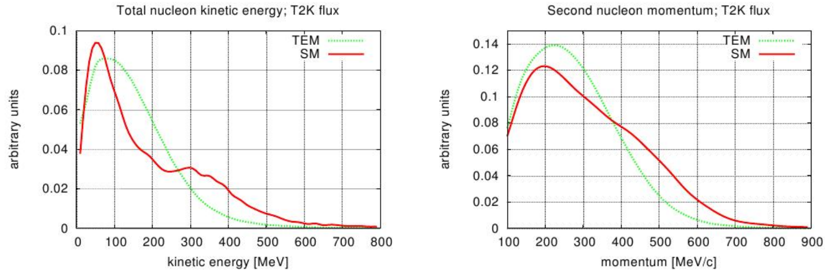
Some predictions (2)





Some predictions (3)

T2K flux averaged:



Monte Carlo implementation

In order to compare to the data one needs MC. FSI effects are very important.

NuWro implementation:

- one of the motivations: GENIE had problems...
- there are two new *dynamics*, flag: mec (CC and NC)
- I started with TEM model, the algorithm is much more efficient
- only CC carbon target
- there are several details on the energy balance which can be made better
- implementation of the SM can be (?) very slow.

Experimental aspects

- of interest are CCQE-like events, with no pions in the final statements; one needs a strong veto on pions
- one must use the information contained in reconstructed proton tracks and in the *vertex activity*
- it is better to have a low threshold for reconstruction proton tracks
- the quality of FSI model is very important, pion absorption seems to be the most important background
- observables like integrated kinetic energy should be less affected by FSI.

IDEA 1: Pairs of reconstructed protons (PRELIMINARY)

T2K flux. Only CC. QE:RES:DIS:COH:MEC = 50:23:14:1:12.
Count proton pairs above a threshold (horizontal). Consider varying charged pion veto (vertical). 100 kiloevents.

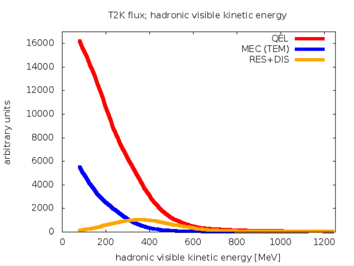
	300	350	400	450	500
0	2008/7664	1274/5928	754/4458	417/3189	198/1893
100	2011/7861	1275/6064	754/4544	417/3247	198/1928
200	2012/9423	1276/7140	754/5218	417/3639	198/2155

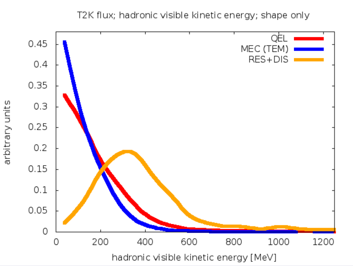
(with the 300 MeV/c threshold for reconstructing proton tracks and with the perfect pion veto there should be 2008 MEC two-proton events and 7664-2008=5656 background two-proton pairs)

IDEA 2: Integrated hadronic kinetic energy (PRELIMINARY)

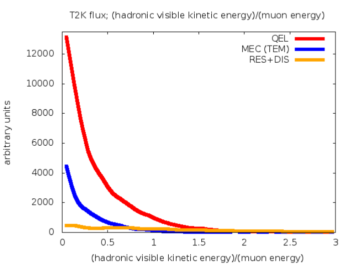
Typical MEC dynamics involves transfers of energy in between QE and Δ peaks.

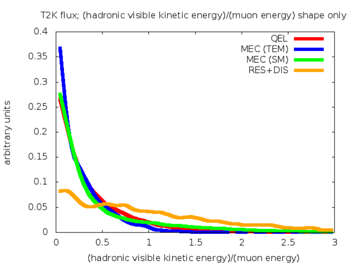
Define two observables: $\sum_j T_j$ and $\frac{\sum_j T_j}{E_\mu}$, where T_j is the kinetic energy of charged hadron. Assume we can veto charged pions.





IDEA 2: Integrated hadronic kinetic energy (PRELIMINARY)





Presumably TEM and SM do not account well for the distribution of energy transfer?

Summary

- there are several indications of a large multinucleon emission contribution to the inclusive CC
- one needs good microscopic models
- one needs a very good nucleon cascade model
- it is important to define observables sensitive enough to provide a proof that the multinucleon emission does really exist

Thank you!