What are CCQE interactions?

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(on sabbatical from the Wrocław University)

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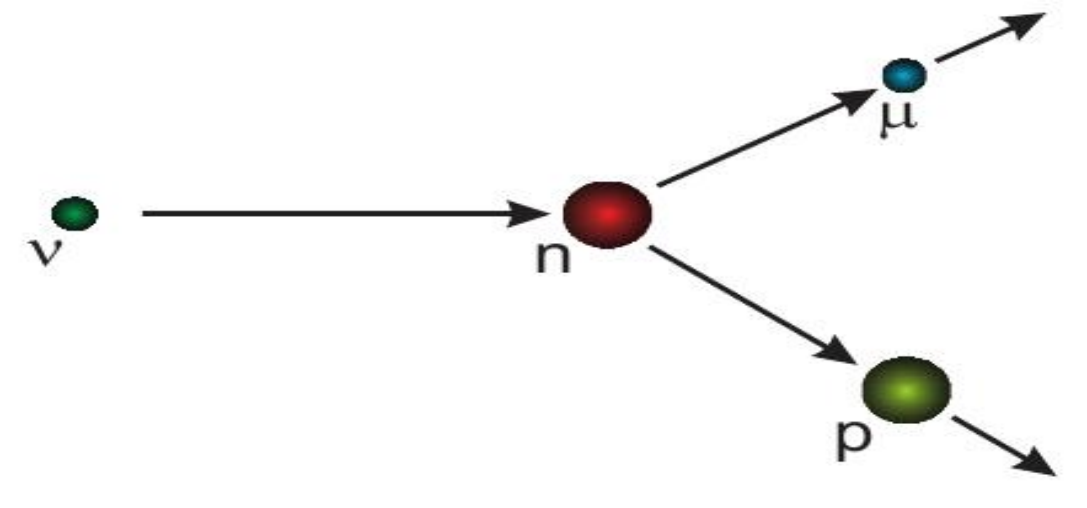
Outline

- free nucleon target
- Impulse Approximation
- basic theory (a few formulas)
- axial mass
- Fermi Gas and Spectral Function
- experimentalist definition of CCQE
- axial mass puzzle; MiniBooNE 2D data
- two-body current - existing models
- two-body current - experimental aspects
  - two proton ejection
  - integrated nucleon kinetic energy

Quasielastic reaction on a free nucleon target

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

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



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

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

Nuclear target reaction

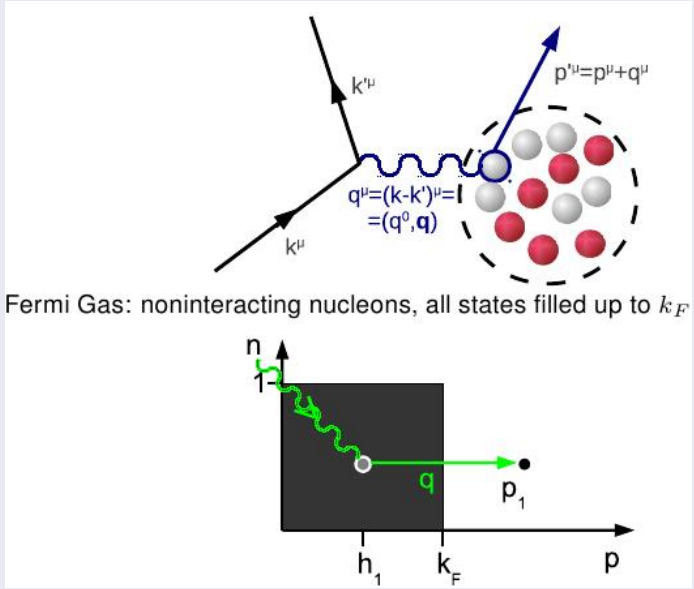
We would like to use the same definition for neutrino-nucleus reaction.

Complications:

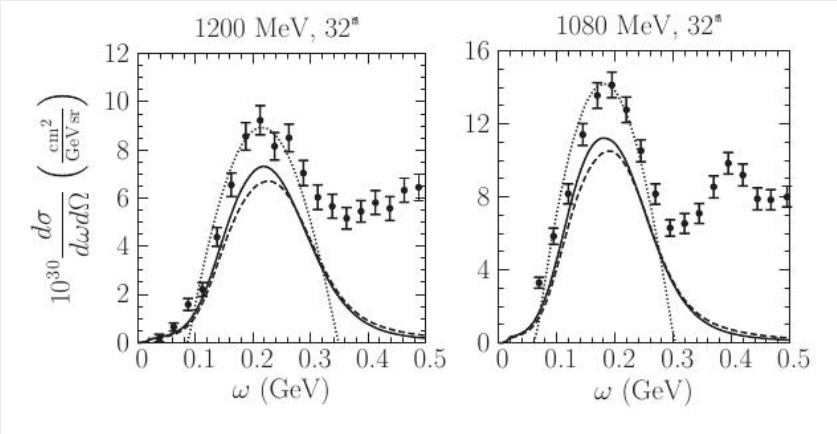
- can we assume that neutrino *sees* nucleus as composed from quasi-free nucleons?
- what is the experimental *definition* of CCQE? Muon and proton in the final state, as before?...

Impulse approximation – Fermi Gas model

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



from Jakub Zmuda

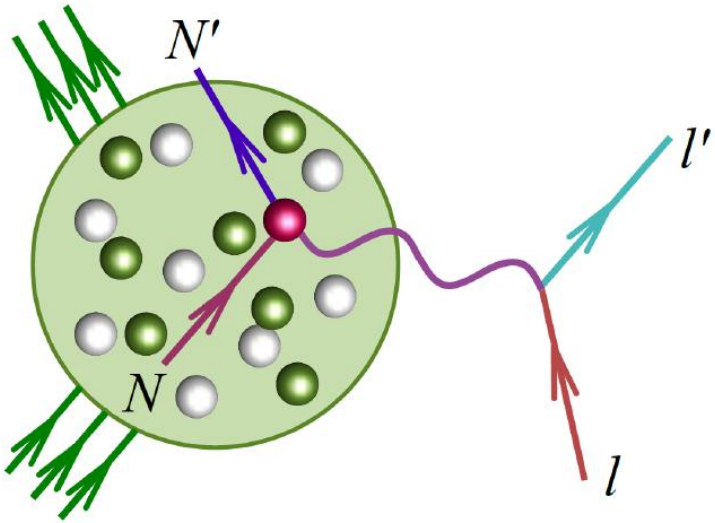


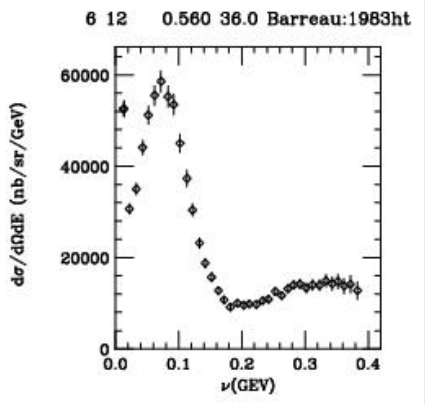
from A. Ankowski, JTS, Phys. Rev C77 (2008) 044311

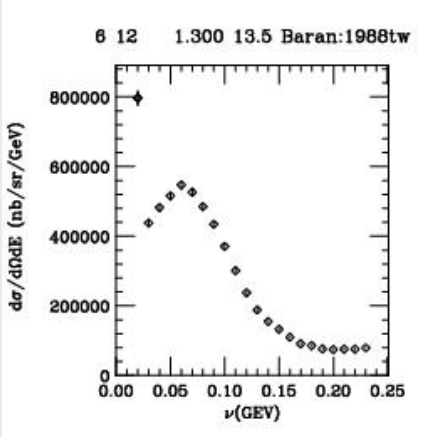
In a wide kinematical region IA works quite well.

Electron energy and scattering angle are fixed.

Impulse Approximation (IA) - limitations







Electron carbon data

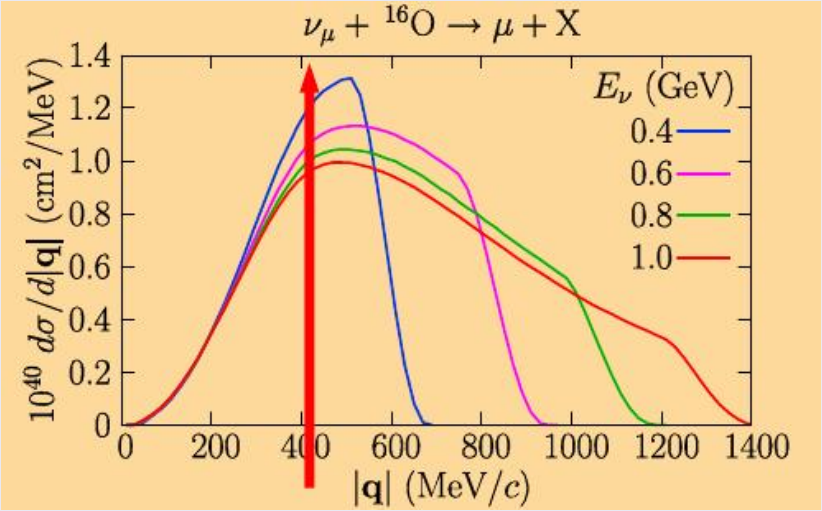
from Artur Ankowski

Think about de Broglie wave and remember 1 fm $= \frac{1}{200\ MeV}$. 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 choose region in which IA works well. Neutrino experiments are always inclusive. How much of the cross section comes 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).

Probably, we should not call them CCQE?!

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)

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

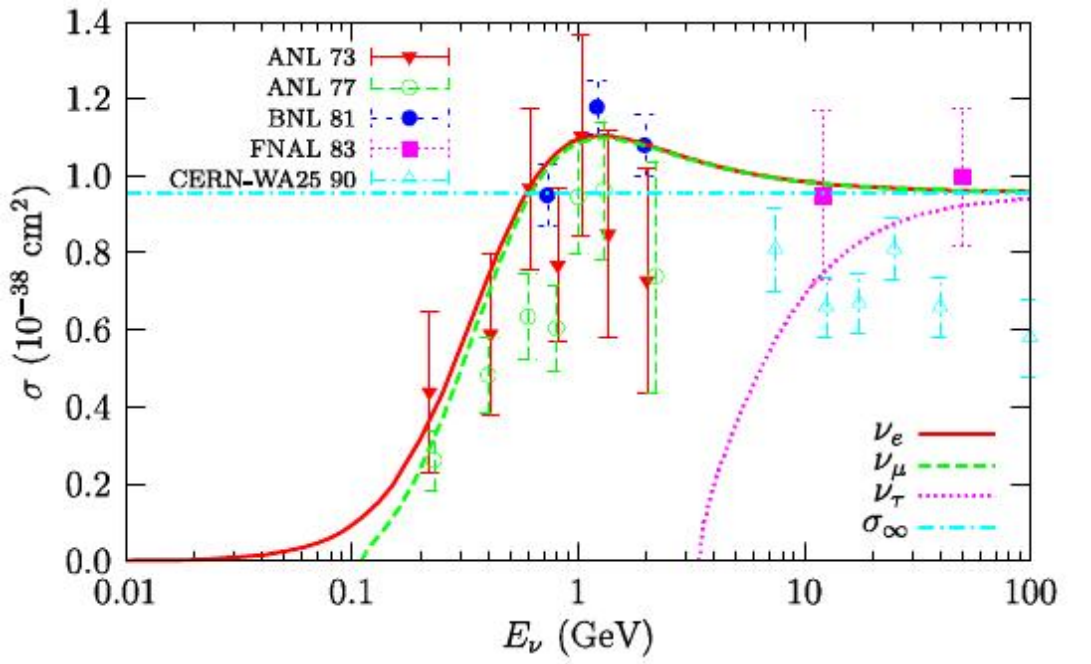
Axial mass

If we accept all that:

- 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.

Total CCQE cross section on a free nucleon

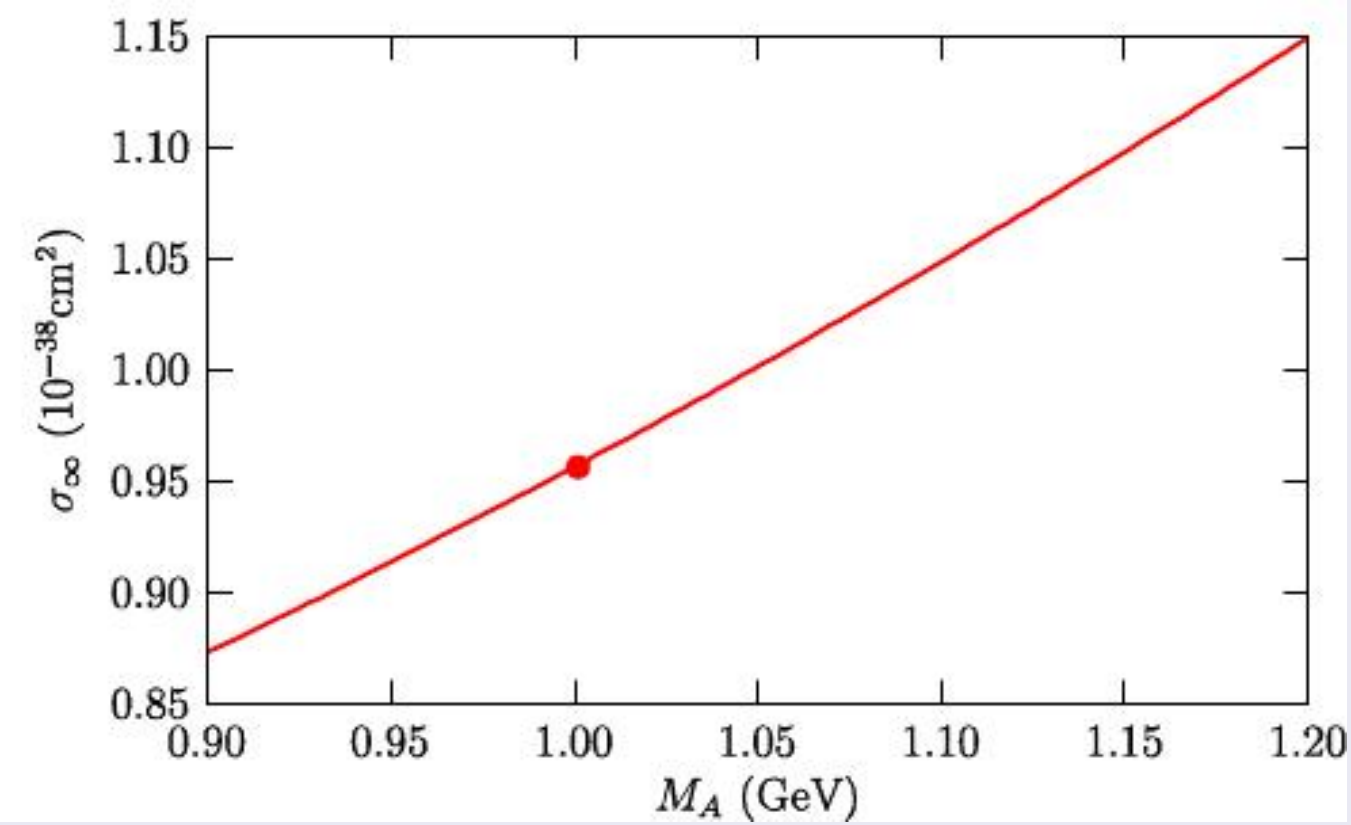
The E dependence is shown below (only old experimental results are included):



- large experimental errors
- at large energy cross section saturates; which is the limiting value?...

from A. Ankowski

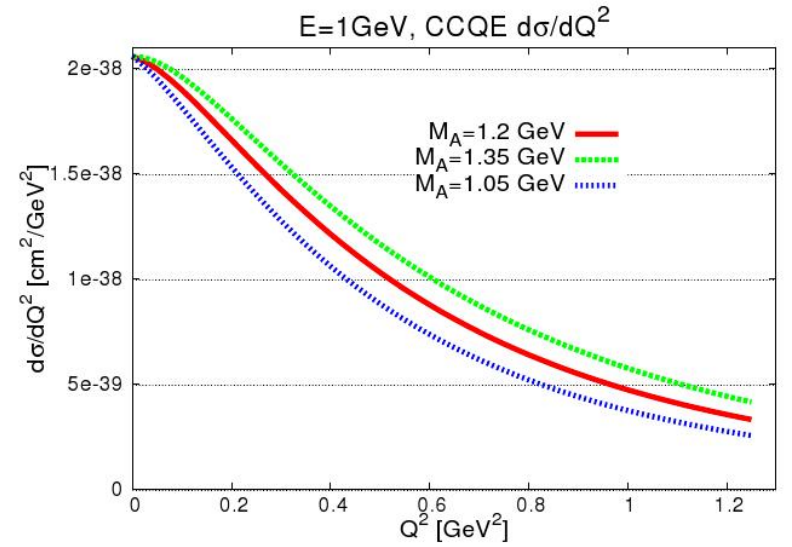
$E \to \infty$ limit

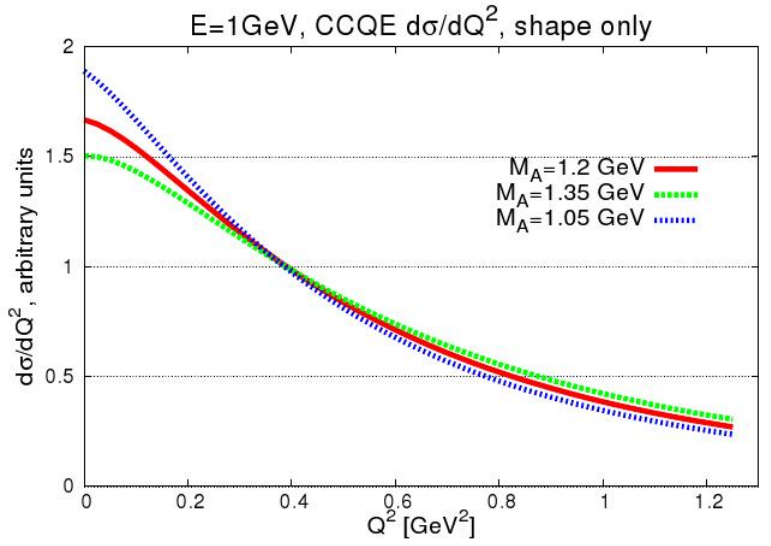


from A. Ankowski

The $\sigma_\infty(E)$ dependence is quadratic but in the relevant region it is $\sim$ linear.

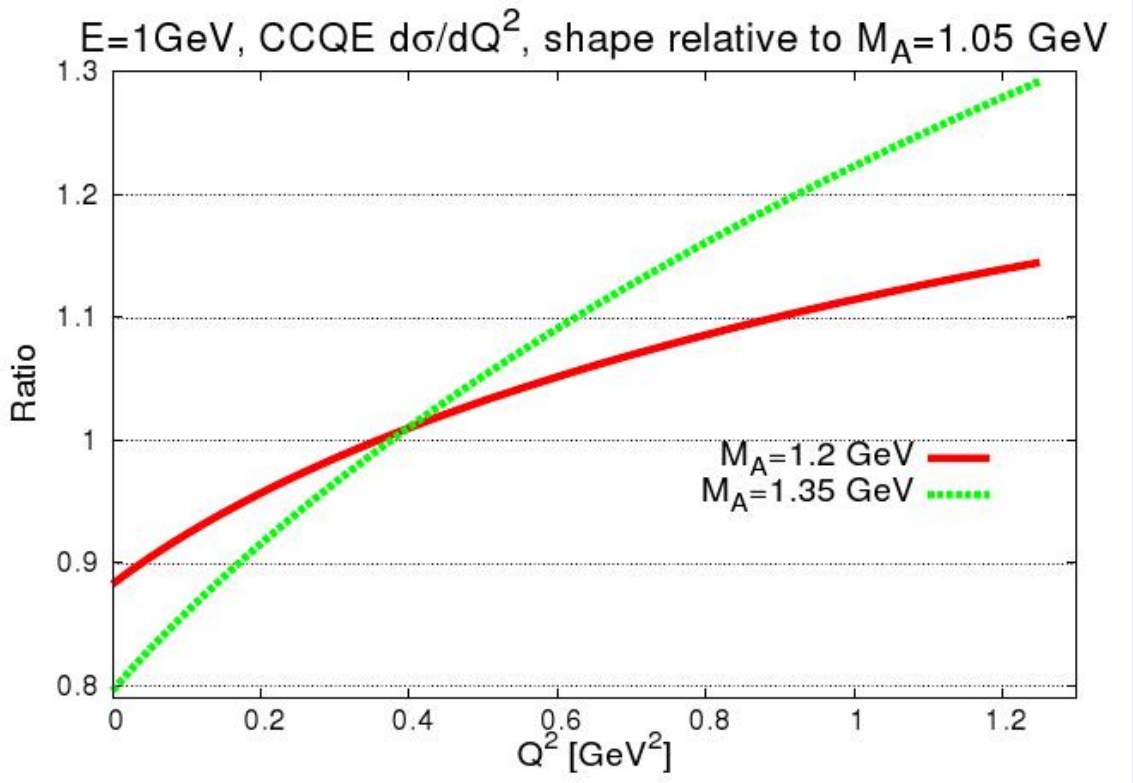
$d\sigma/dQ^2$ dependence on M_A





$d\sigma/dQ^2$ dependence on M_A

If M_A is raised from 1.05 GeV to 1.35 GeV, the shape of $\frac{d\sigma}{dQ^2}$ is dramatically changed:

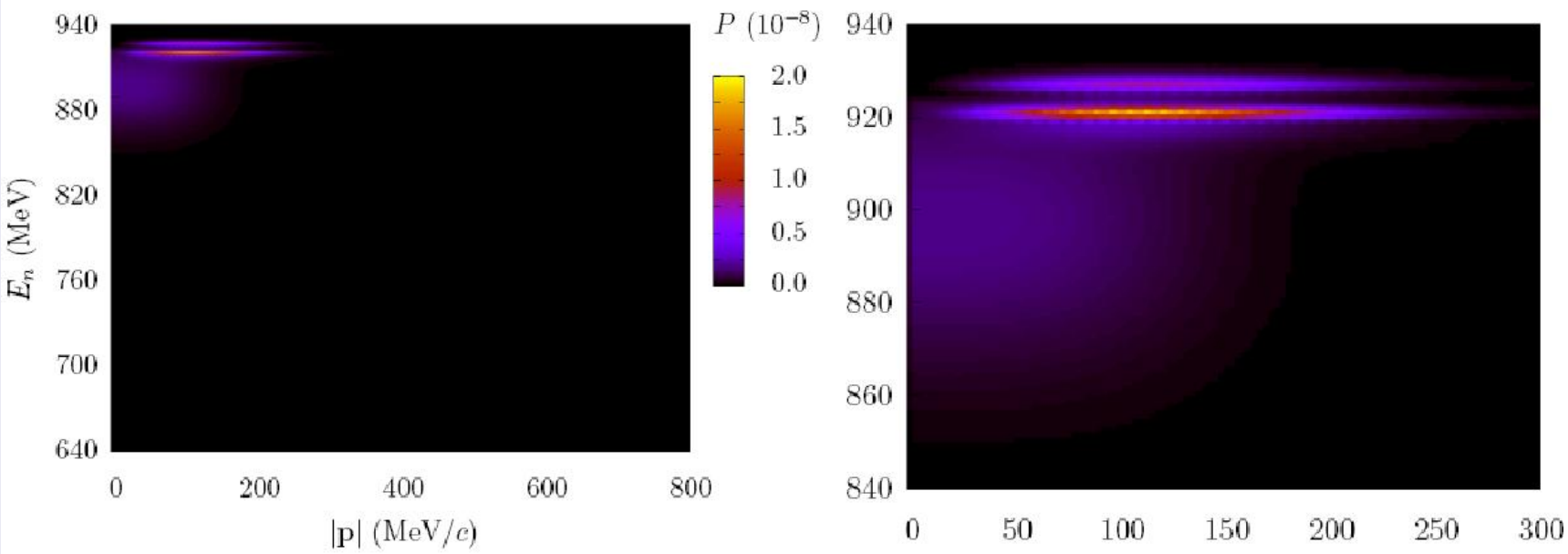


Relative number of events at large Q^2 is raised by $\sim 30\%$

Nuclear model for IA

Monte Carlo event generators rely on Fermi Gas model. But there is much better model: Spectral Function!

Below, the oxygen SF calculated by Omar Benhar:



Shell model orbitals are clearly seen.

	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$
E	45	18.44	12.11

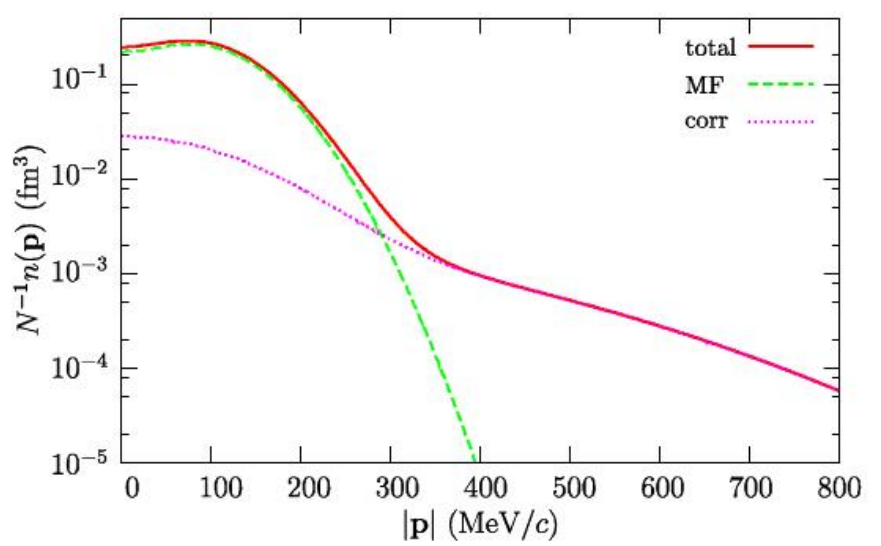
Fermi Gas and Spectral Function

SF contains a lot of information about nucleus:

$$n(\vec{p}) = \int dE\ P(E,\vec{p}) = \sum_R |< R(p_R)|a(\vec{p})|i(M_A) >|^2 =$$

$$=< i(M_A)|a^\dagger(\vec{p})a(\vec{p})|i(M_A) >$$

is the nucleons momentum distribution.



- mean field (MF) and SRC (corr) contributions are shown separately.
- high momentum tail, absent in the FG model, comes from correlated nucleon pairs.

Spectral Function in action

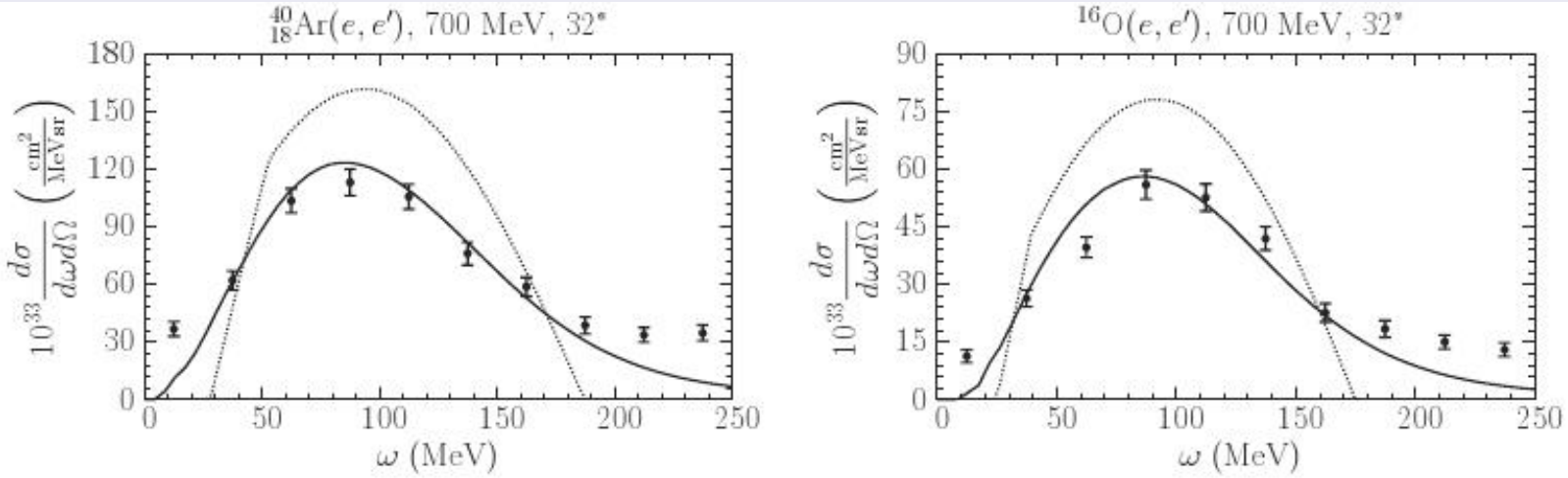


FIG. 7. (Left panel) Comparison of the cross section of GSF (solid line) and the FG model (dotted line) with experimental points for Ar(e, e') at beam energy 700 MeV and scattering angle 32° [7]. (Right panel) Same but for oxygen. Note that in both cases the similar accuracy is obtained. The value of momentum transfer at the peaks is 371 MeV.

[from: A.M. Ankowski, JTS, Phys. Rev. C 77 044311 (2008)]

Typically, SF based computations reproduce better QE peak.

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

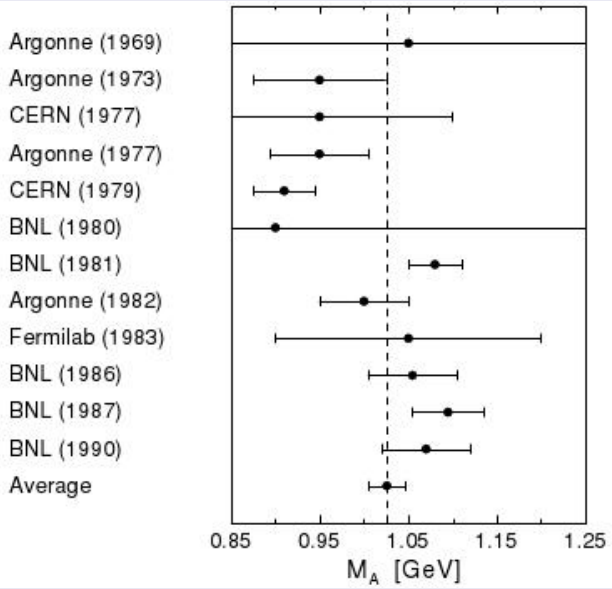
QE reaction on nuclear target - NOMAD

- 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?!...

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.

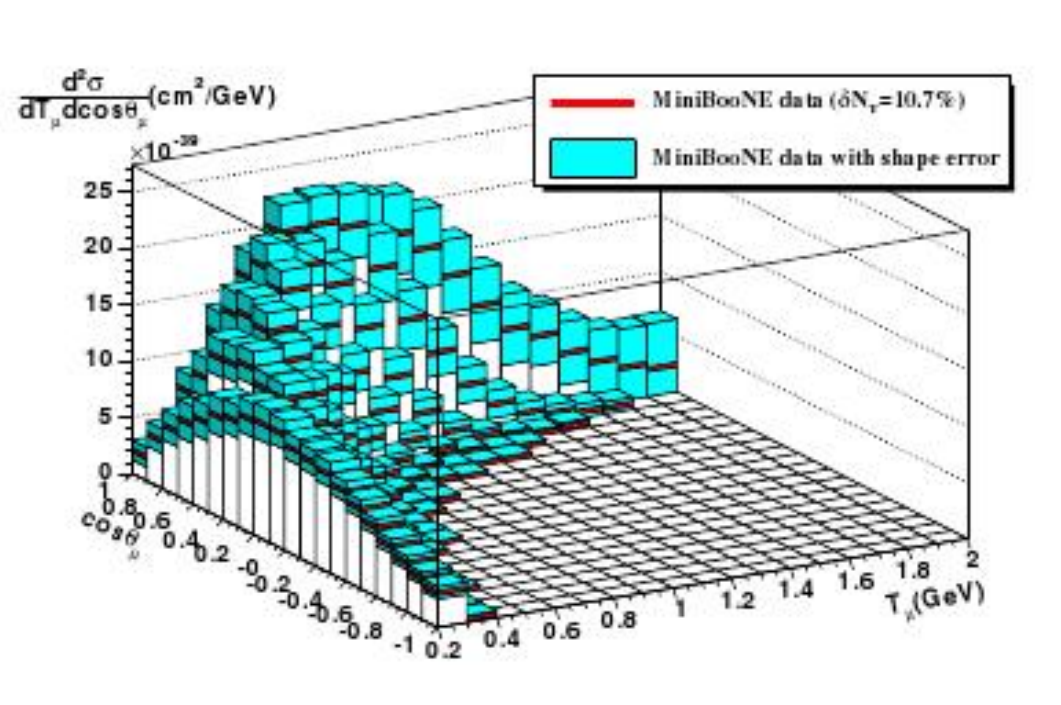


[from Bernard, Elouadrhiri, Meissner]

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

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:



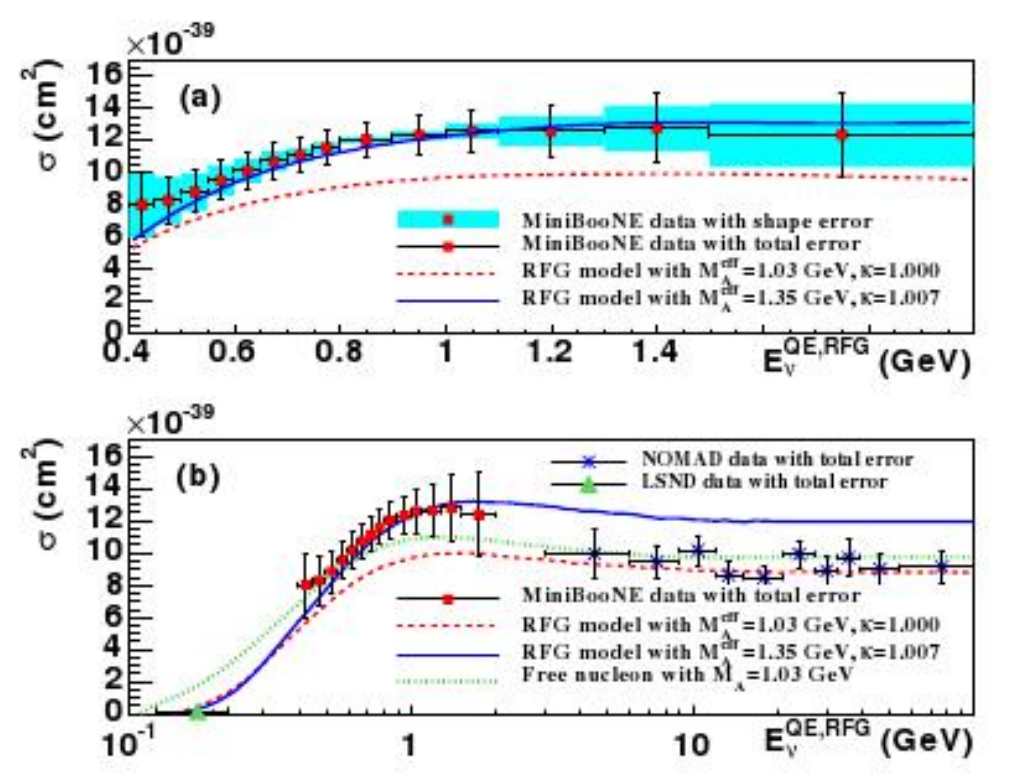
A.A. Aguilar-Arevalo et al.,[MiniBooNE collaboration] Phys. Rev. D81, 092005 (2010)

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!

What is there in the MB signal?

The main background comes form the pion absorption. But this was subtracted from the CCQE-like sample of events.

Hypothesis: there is a large multinucleon contribution to the inclusive CC cross section.

We go beyond the Impulse Approximation with the introduction of the **two-body current**.

Basic intuition

Remember

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

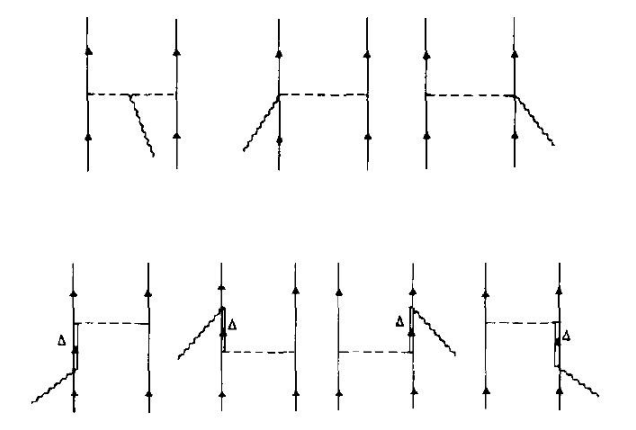
In the second quantization language J^{α} is an operator which annihilates (removes from the Fermi see, producing a HOLE) nucleon with momentum p, and creates (above the Fermi level) particle with momentum p':

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

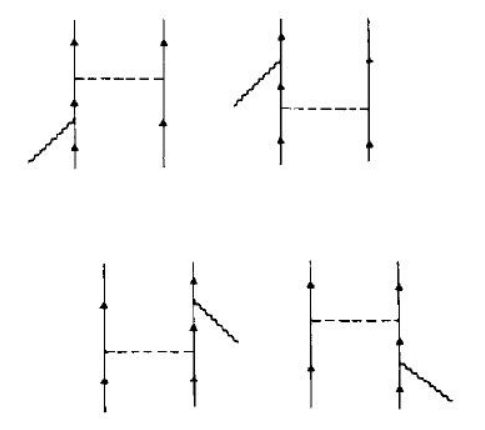
Basic intuition

Think about the following more complicated diagrams:

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



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



correlation diagrams

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

creates two holes and two particles (2p-2h).

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

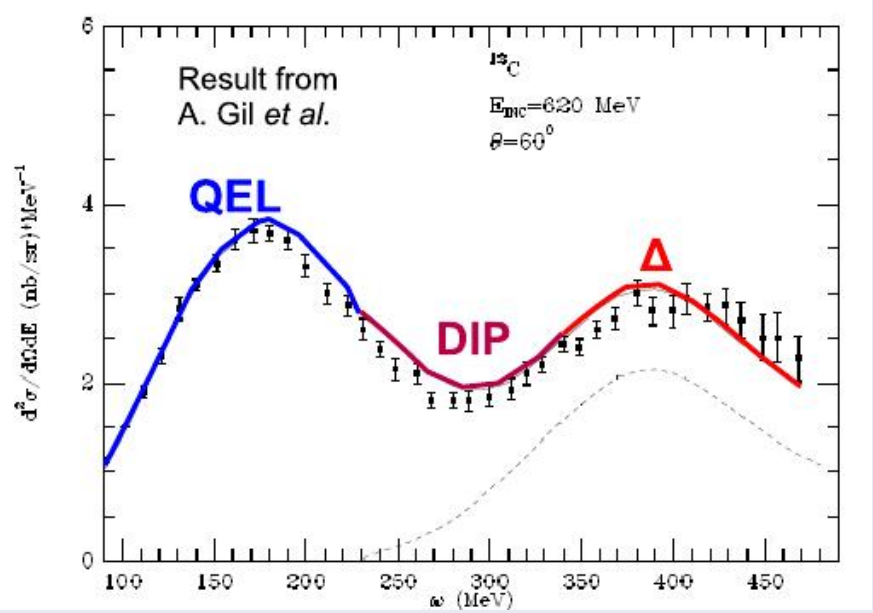
There are also effective models:

- 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.

Models predictions - a one slide detour

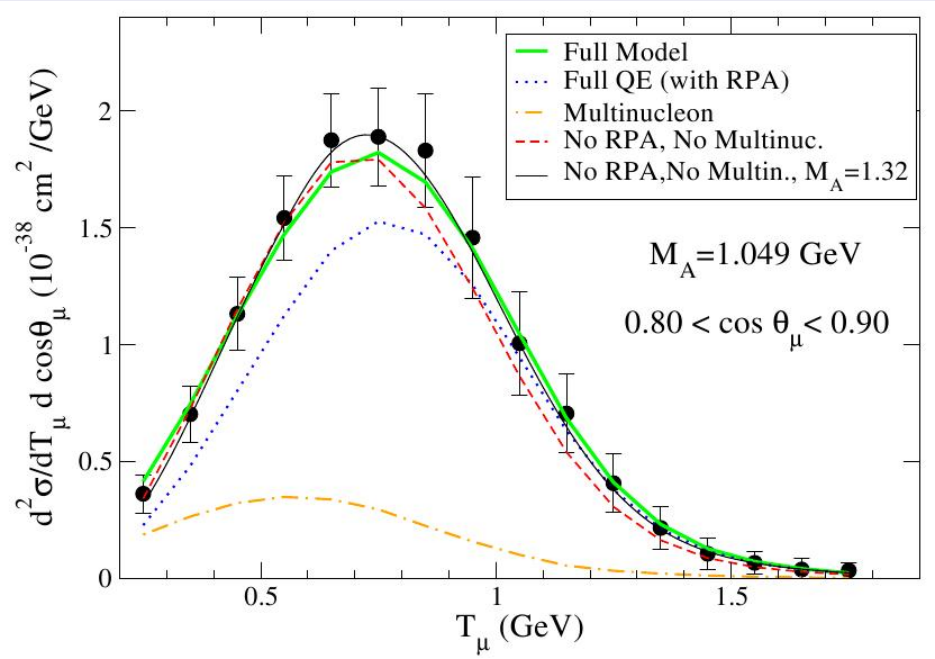
In the electron scattering community there have been a problem of access of the cross section in the DIP region between QE and Δ peaks:



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

- there is about 30 years long discussion on the *DIP* region (see left)
- the extra strength is believed to come from two-body currents

Model predictions



On the horizontal axis is muon energy, not the energy transfer! According to the electron scattering intuition MEC is *on the left* from the QE peaks (on the previous slide it was on the right!

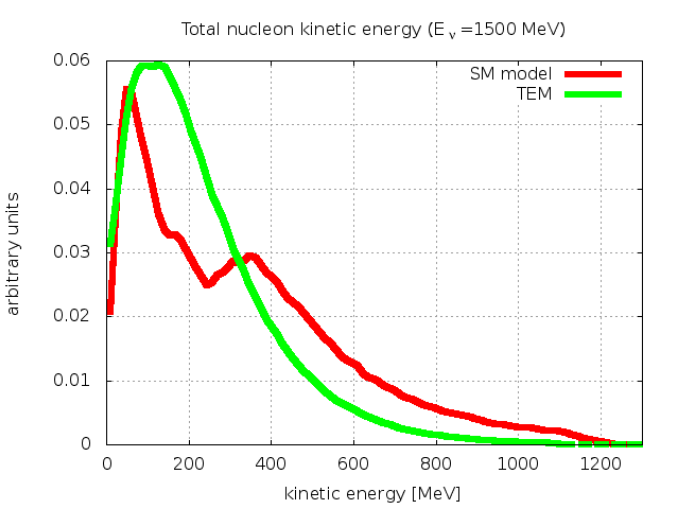
But the direct proof can come only from hadronic observables!

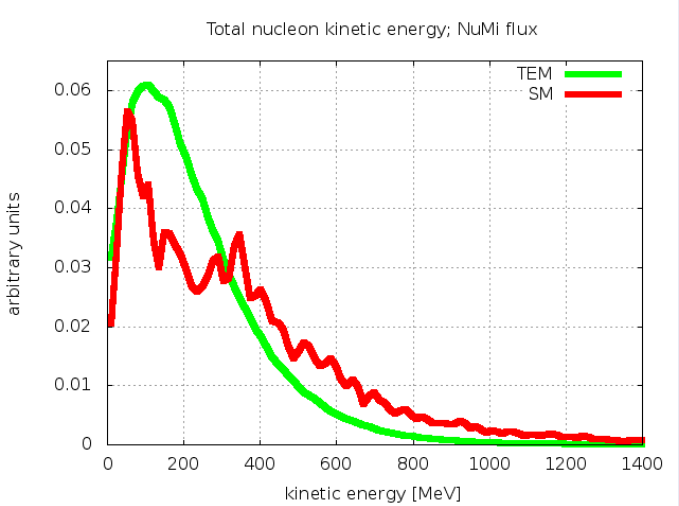
Experimental aspects

- 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 are less affected by FSI.

Some predictions (1)

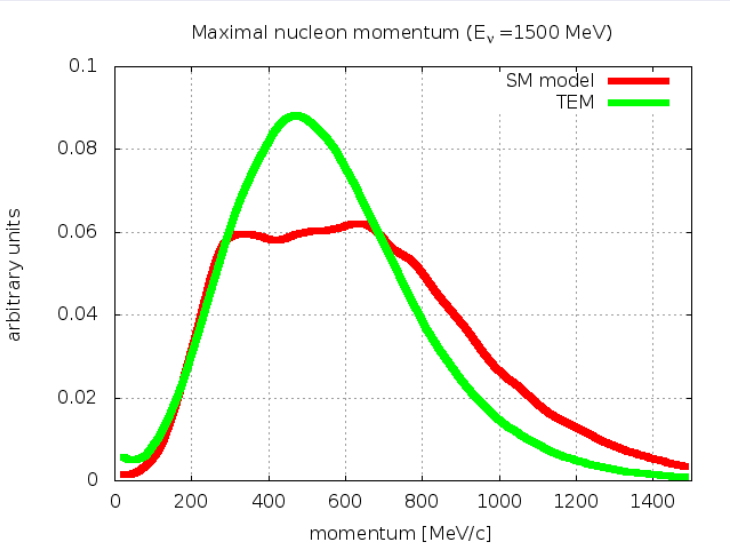
In order to produce hadronic predictions we need a model, preferable in a MC event generator.
Typically, I show predictions from two different models for MEC contribution: simplified Marteau (SM) and Transverse Enhancement Model (TEM).

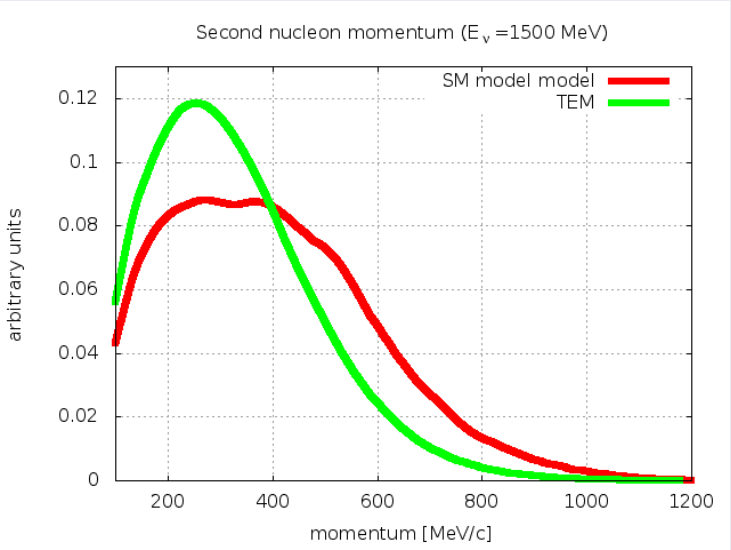




This can be seen as a vertex activity

Some predictions (2)

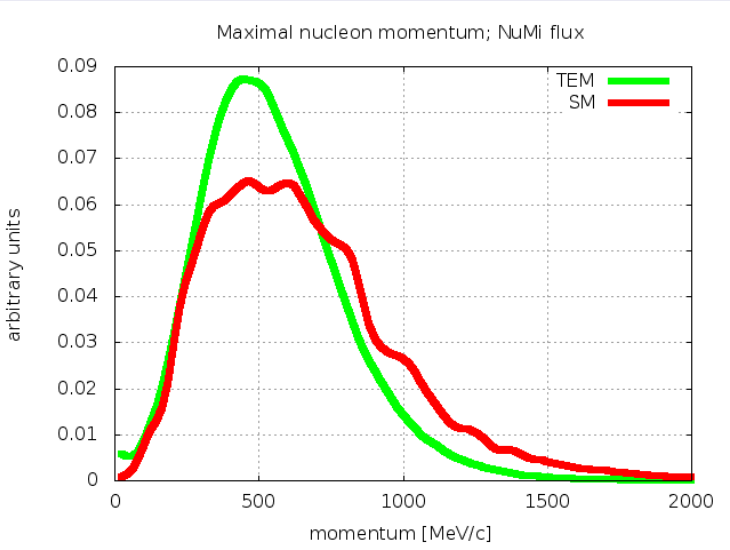


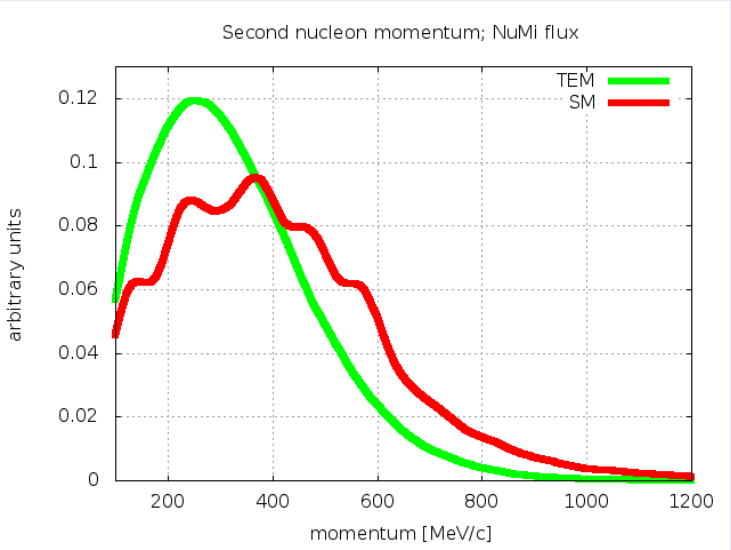


If the second nucleon is energetic enough we can see two protons in one event.

Some predictions (3)

NuMi flux averaged:





IDEA 1: Pairs of reconstructed protons (PRELIMINARY)

NuMi flux. Only CC. TEM model.
QE : RES : DIS : COH : MEC = 16 : 23.5 : 56.5 : 1 : 3.
Count proton pairs above a threshold (horizontal). Consider varying charged pion veto (vertical). 100 kiloevents.

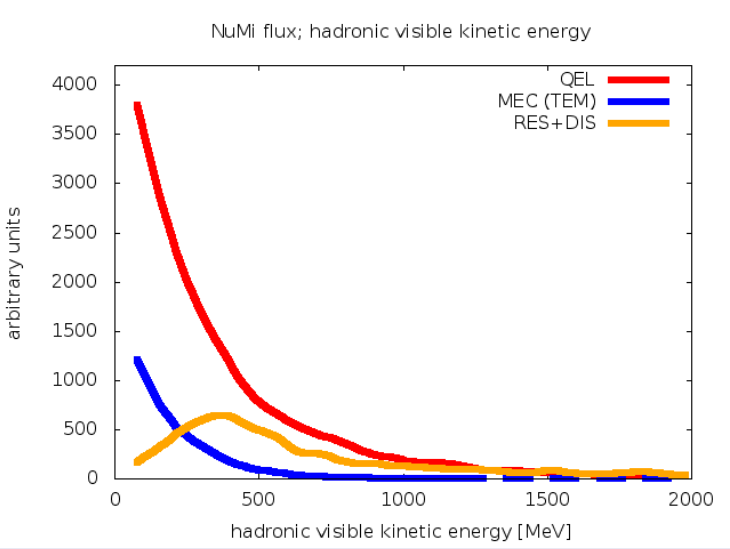
	300	350	400	450	500
0	1330/5620	948/5304	682/5076	476/4510	334/3482
100	1334/5960	952/5594	684/5304	478/4680	336/3610
200	1336/8306	954/7482	686/6762	480/5762	338/4346

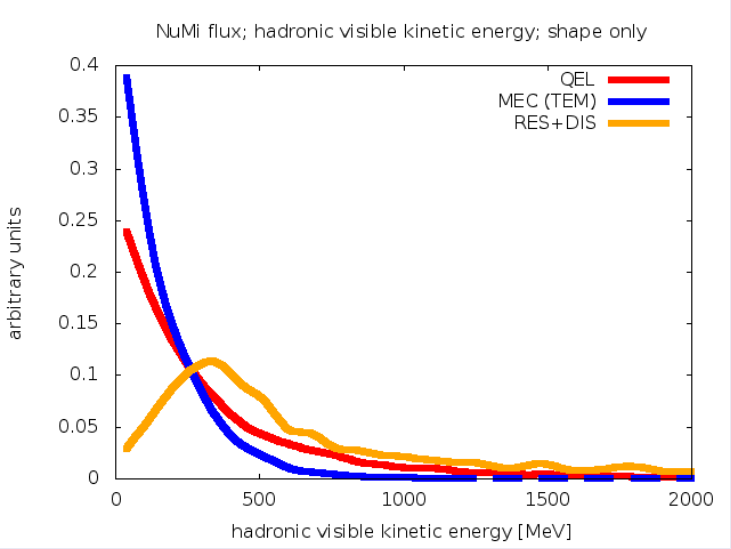
(with the 300 MeV/c threshold for reconstructing proton tracks and with the perfect pion veto there should be 1330 MEC two-proton events and 5620-1330=4290 background two-proton pairs)

IDEA 2: Integrated hadronic kinetic energy (PRELIMINARY)

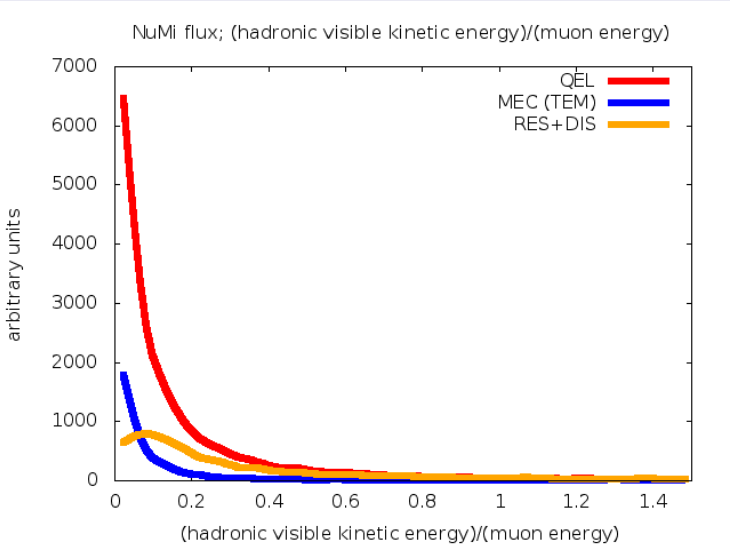
Typical MEC dynamics involves transfers of energy in between QE and Δ peaks.

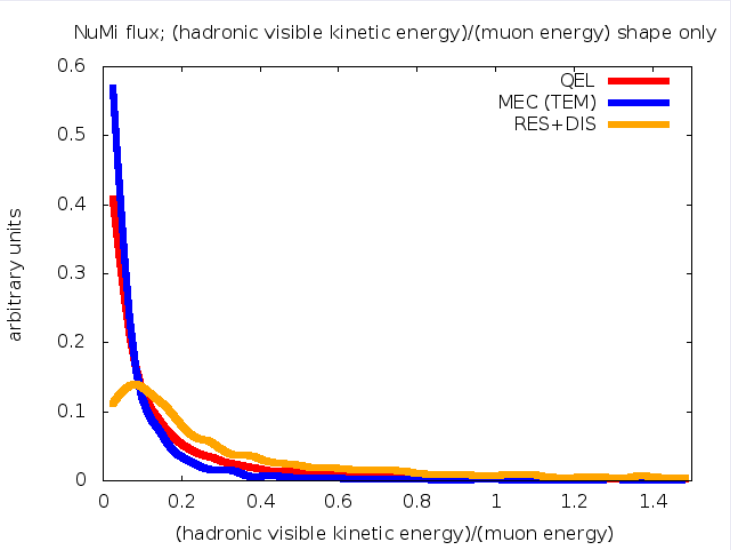
Define two observables: $\sum_j T_j$ and $\frac{\sum_j T_j}{E_\mu}$, where T_j is the kinetic energy of charged hadron. Assume we can perfect veto on charged pions.





IDEA 2: Integrated hadronic kinetic energy (PRELIMINARY)





Deos SM account well for the distribution of energy transfer?

Outlook

- CCQE on a free nucleon target – a little boring, fitting one parameter M_A
- CCQE on a nuclear target – more exiting, nontrivial nuclear effects
- study of CCQE-like events (no pions in the final state) – really interesting, a hope to discover the new dynamical mechanism!

Thank you!

Back-up slides:

Non dipole axial form factor

In early years of neutrino experiments non-dipole axial FF were considered motivated by quark model vector-dominance (QM V-D)

L.M. Sehgal (1979)

$$F_A(Q^2) = \frac{F_A(0)}{1 + \frac{Q^2}{M_A^2}} \cdot \exp\left(-\frac{Q^2[GeV^2]}{1 + \frac{Q^2}{4M^2}}\right),$$

Various analysis produced the following results for M_A:

Experiment	"Dipole" M_A	"QM V-D" M_A
SKAT (1990)	$1.06 \pm 0.05 \pm 0.14$ (ν)	1.22 ± 0.14
	$0.71 \pm 0.10 \pm 0.20$ ($\bar{\nu}$)	
Serpukhov (1985)	1.00 ± 0.04	1.11 ± 0.10
BNL (1981)	1.07 ± 0.06	1.31 ± 0.16
ANL (1982)	1.00 ± 0.05	1.11 ± 0.16

Comparison of two fits

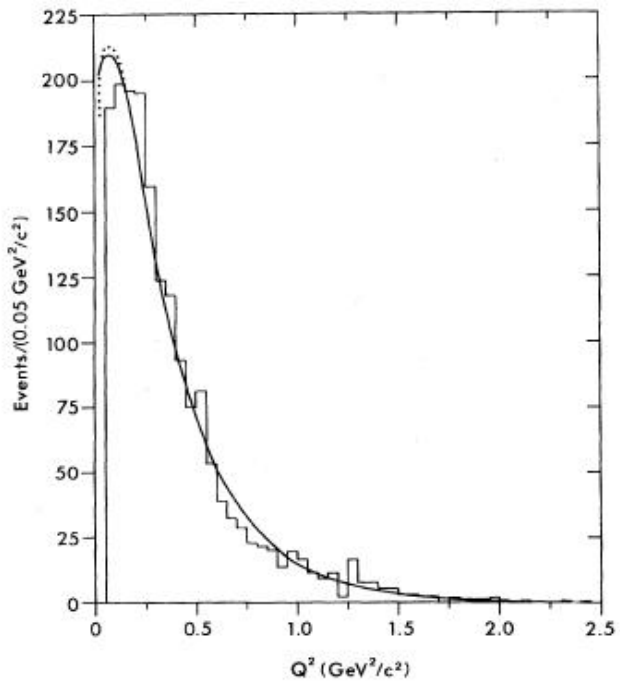


FIG. 4. Weighted Q^2 distribution. The solid curve is from a maximum-likelihood fit to the dipole model ($M_A = 1.00$ GeV/c^2). The dotted curve is from a fit to the AVMD model ($M_A = 1.11$ GeV/c^2).

The QM V-D fit is better by one standard deviation!

ANL

Non dipole axial form factor - references

[SKAT] J. Brunner et al, Z.Phys. C45, 551 (1990)

[Serpukhov] S.V. Belikov et al, Z.Phys. A320, 625 (1985)

[BNL] N.J. Baker et al, Phys. Rev. D23, 2499 (1981)

[ANL] K.L. Miller et al, Phys. Rev D26, 537 (1982)

Non dipole axial form factor

Also monopole and tripole expressions

$$F_A^{monopole}(Q^2) = \frac{F_A(0)}{1+\frac{Q^2}{M_A^2}}, \quad F_A^{tripole}(Q^2) = \frac{F_A(0)}{(1+\frac{Q^2}{M_A^2})^3}$$

were confronted with the data:

Experiment	"Monopole" M_A	"Tripole" M_A
BNL	0.57 ± 0.05	
ANL	0.54 ± 0.05	1.31 ± 0.07

Both [monopole and tripole] gave worse fits than obtained from the dipole form by at least 1.5 standard deviations